Inconsistency Management in Model-Based Systems Engineering

GLOBAL PRODUCT DATA INTEROPERABILITY SUMMIT 2014

ELYSIUM Parker NORTHROP GRUMMAN BOEING

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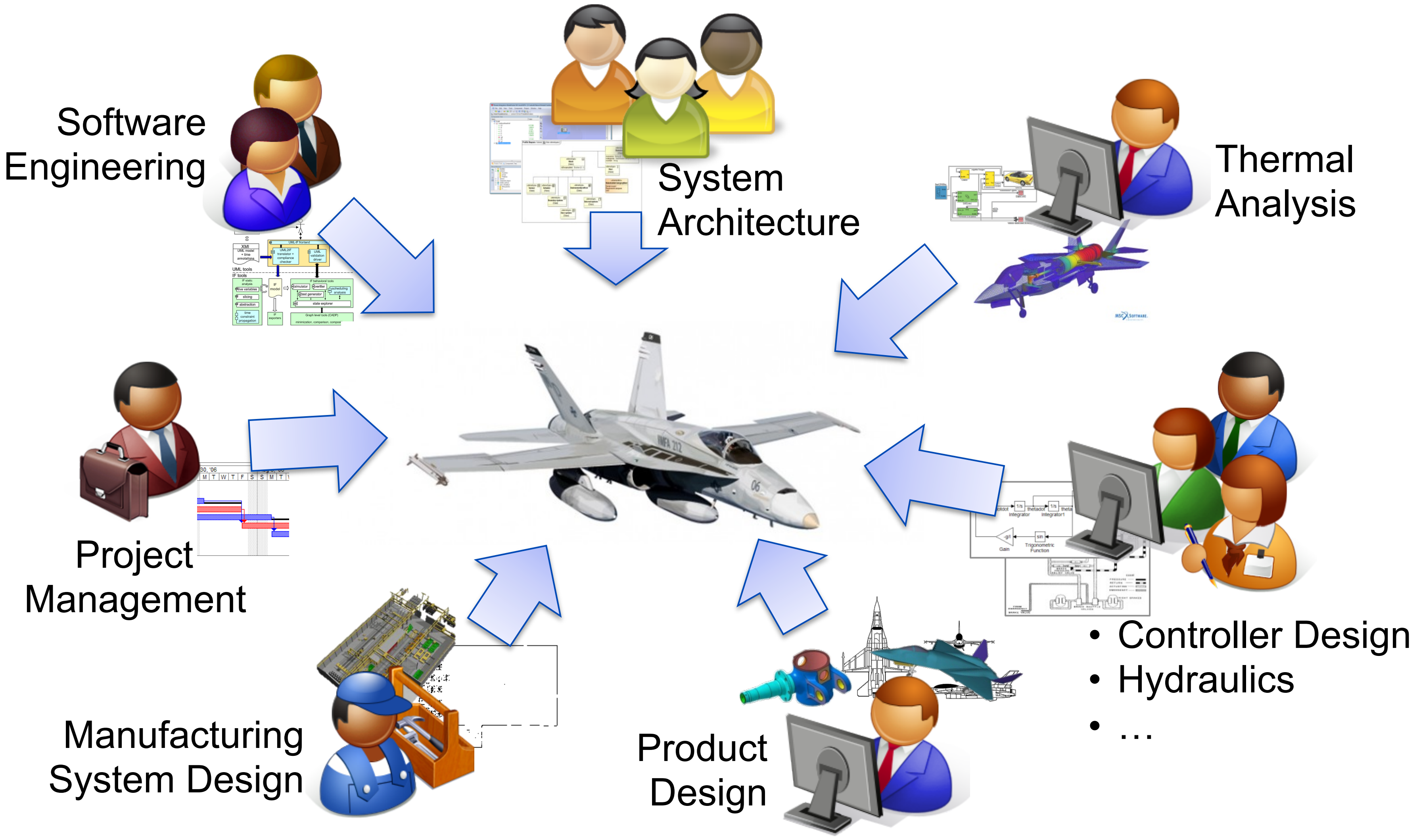
Collaborative, Model-Based Design & Development



Software Engineering

System Architecture

Thermal Analysis

Project Management

- Controller Design
- Hydraulics
- …

Manufacturing System Design

Product Design

Overlapping Concerns

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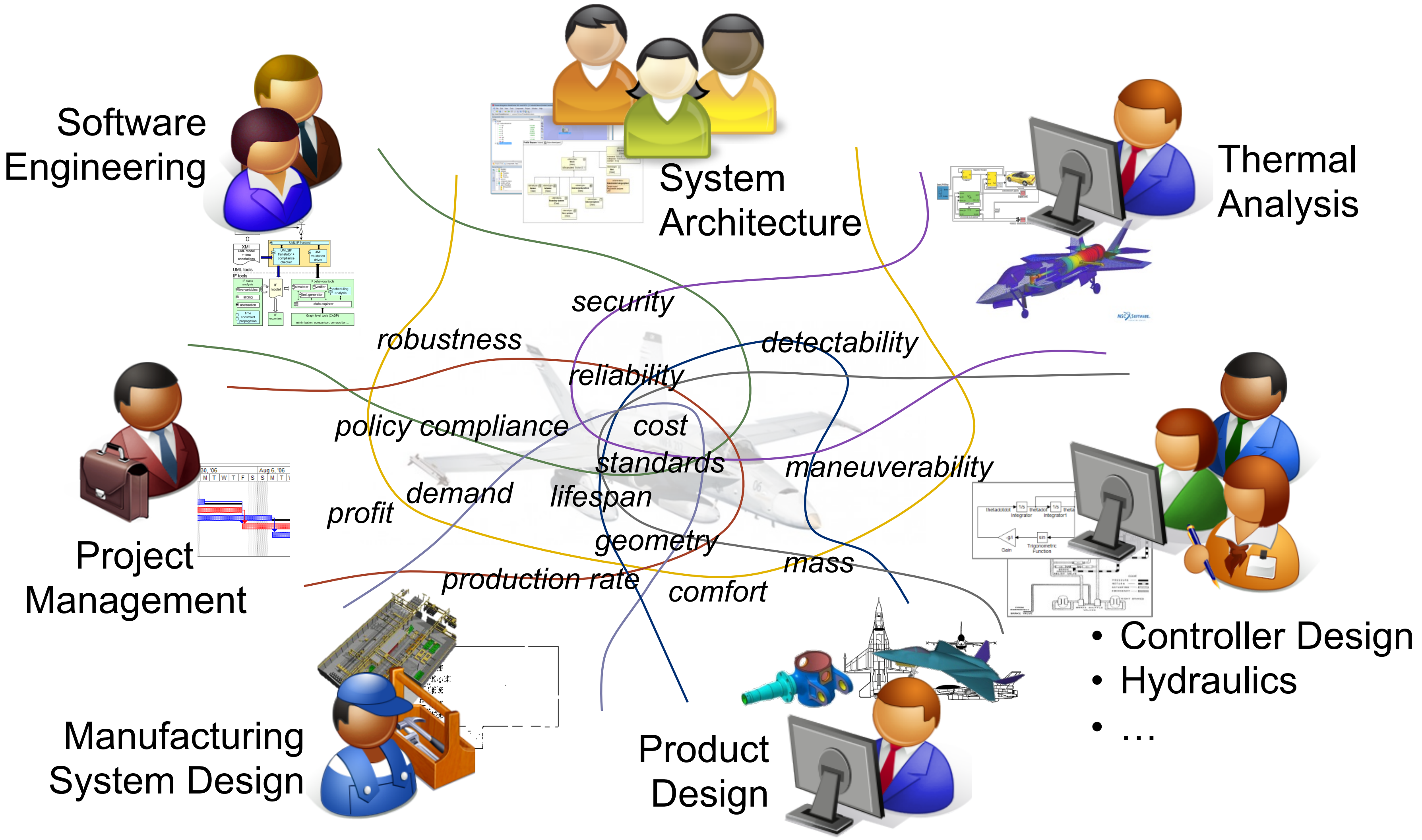

Software Engineering

System Architecture

Thermal Analysis

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Manufacturing System Design

Product Design

- Controller Design
- Hydraulics
- …

security

robustness

detectability

reliability

policy compliance

cost

standards

maneuverability

demand

lifespan

profit

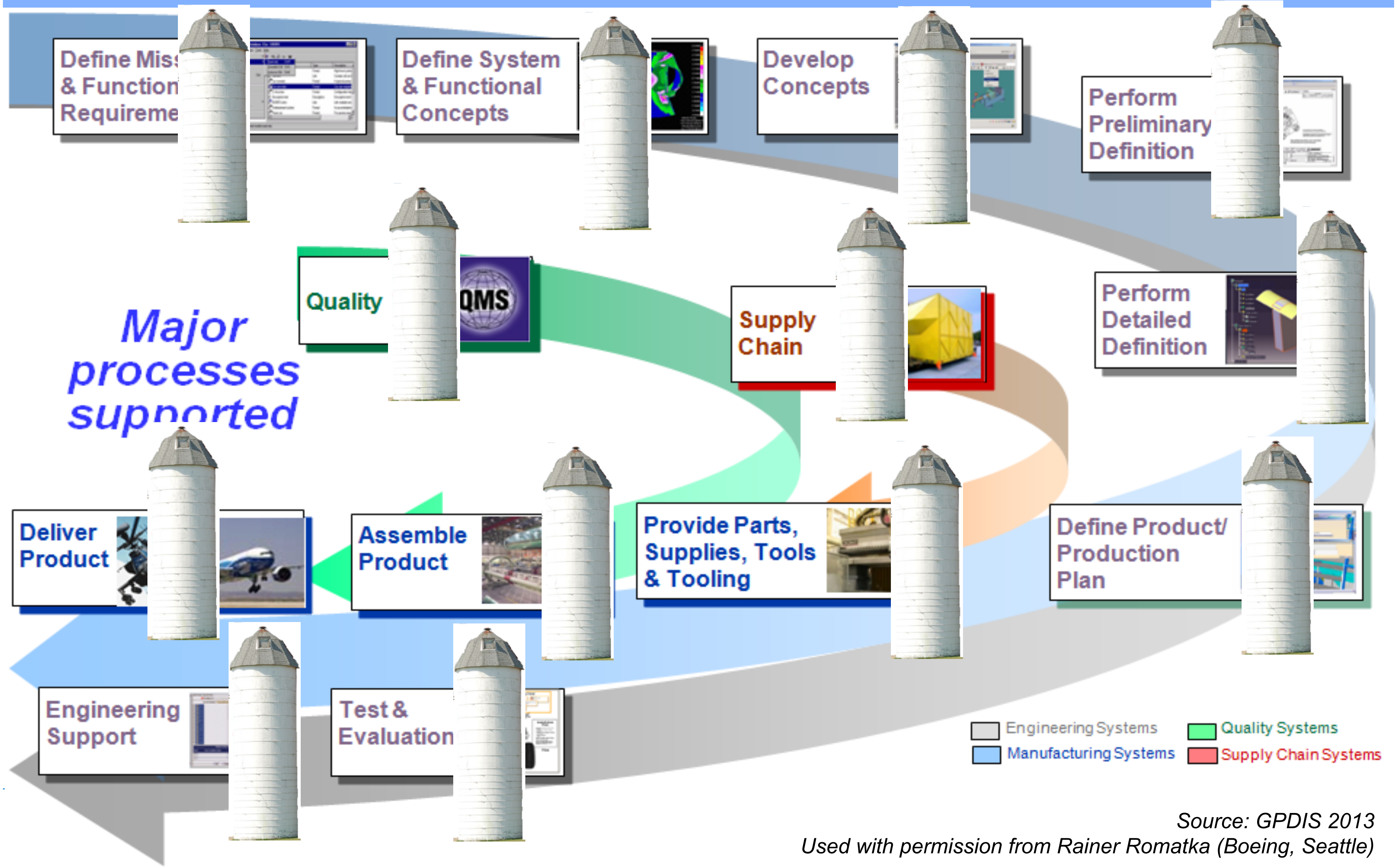
geometry

mass

production rate

comfort

Situation



Define Miss
& Function
Requireme

Define System
& Functional
Concepts

Develop
Concepts

Perform
Preliminary
Definition

Major processes supported

Quality

QMS

Supply
Chain

Perform
Detailed
Definition

Deliver
Product

Assemble
Product

Provide Parts,
Supplies, Tools
& Tooling

Define Product/
Production
Plan

Engineering
Support

Test &
Evaluation

⬜ Engineering Systems
🟩 Quality Systems
🟦 Manufacturing Systems
🟥 Supply Chain Systems

Source: GPDIS 2013
Used with permission from Rainer Romatka (Boeing, Seattle)

Typical Scenario

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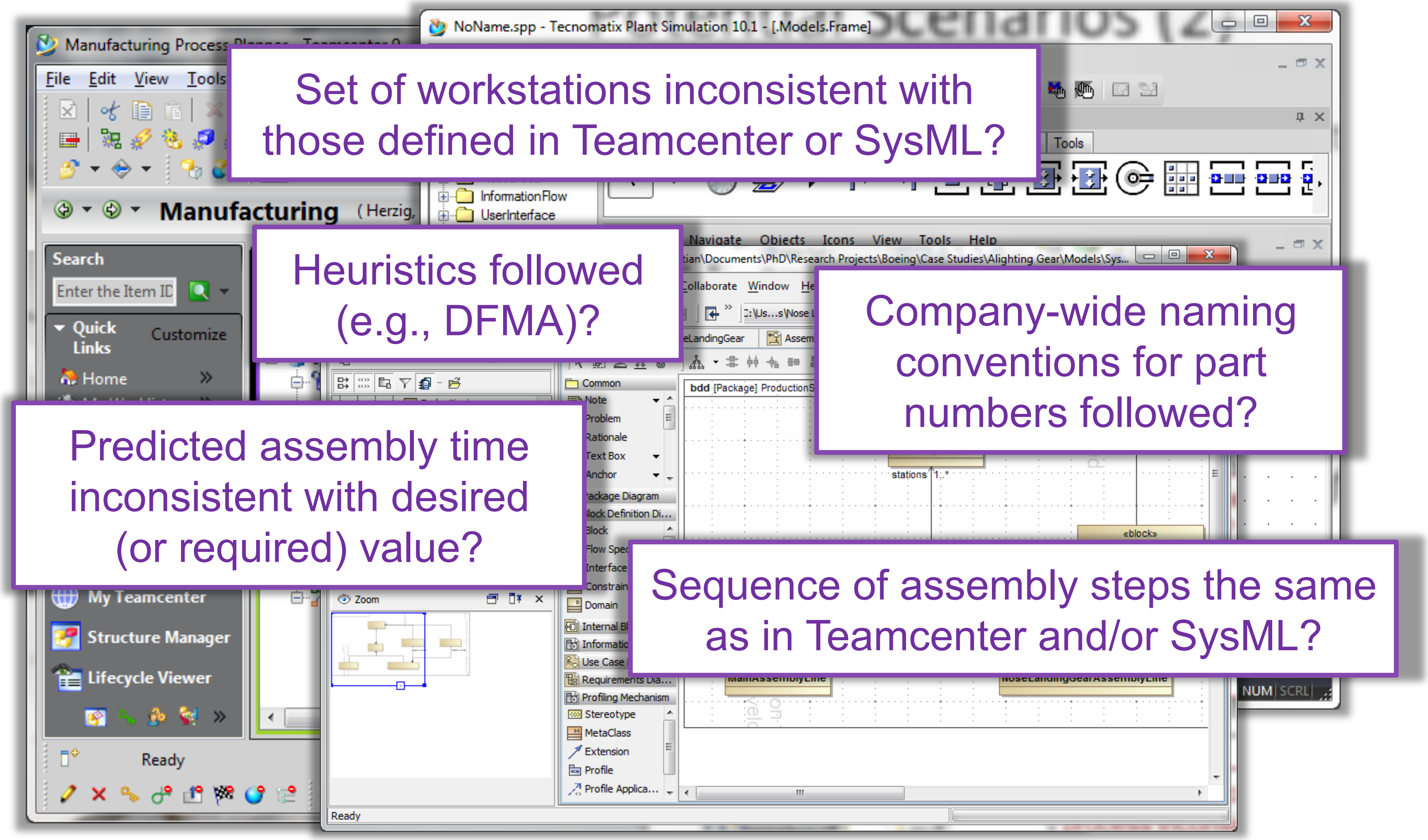

Set of workstations inconsistent with those defined in Teamcenter or SysML?

Heuristics followed (e.g., DFMA)?

Company-wide naming conventions for part numbers followed?

Predicted assembly time inconsistent with desired (or required) value?

Sequence of assembly steps the same as in Teamcenter and/or SysML?

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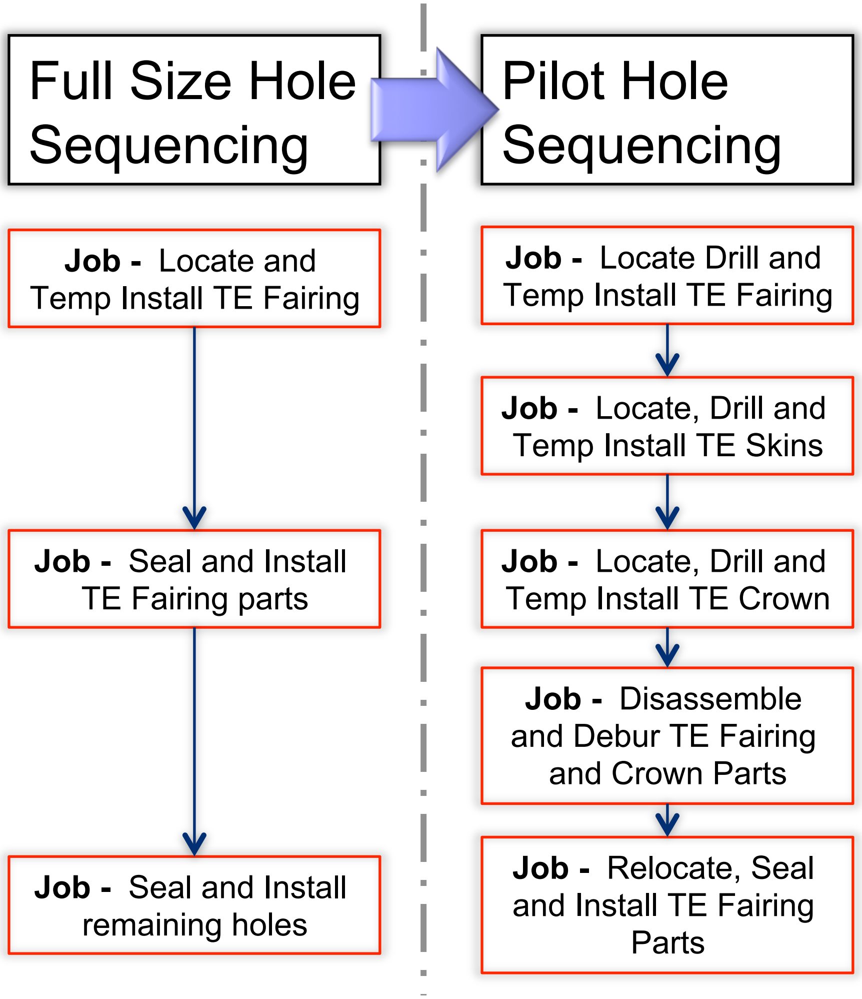
Another Scenario: CM in Design & Development

- **Change in requirements or design: how do changes propagate? Which models are inconsistent as a result?**
- **Example: changing *full holes* to *piloted holes* in a pylon assembly**
  - Affects manufacturing process, optimal shop floor layout for workstations
  - Affects ergonomics models
  - Affects cost models
  - ...



Full Size Hole Sequencing

Job - Locate and Temp Install TE Fairing

Job - Seal and Install TE Fairing parts

Job - Seal and Install remaining holes

Pilot Hole Sequencing

Job - Locate Drill and Temp Install TE Fairing

Job - Locate, Drill and Temp Install TE Skins

Job - Locate, Drill and Temp Install TE Crown

Job - Disassemble and Debur TE Fairing and Crown Parts

Job - Relocate, Seal and Install TE Fairing Parts

Adapted from a scenario provided by Michael Christian (Boeing, St. Louis)

Relationships Between Models

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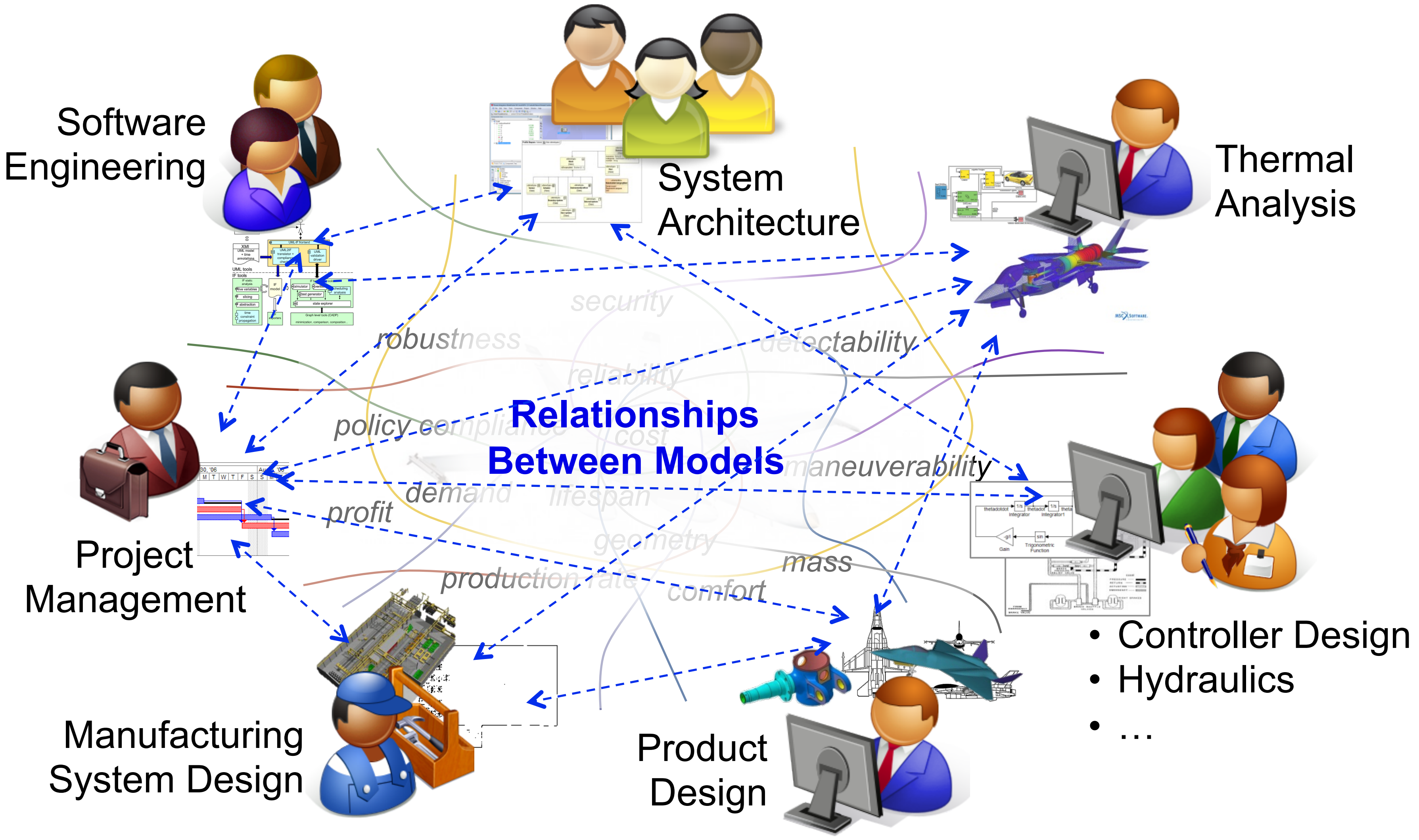

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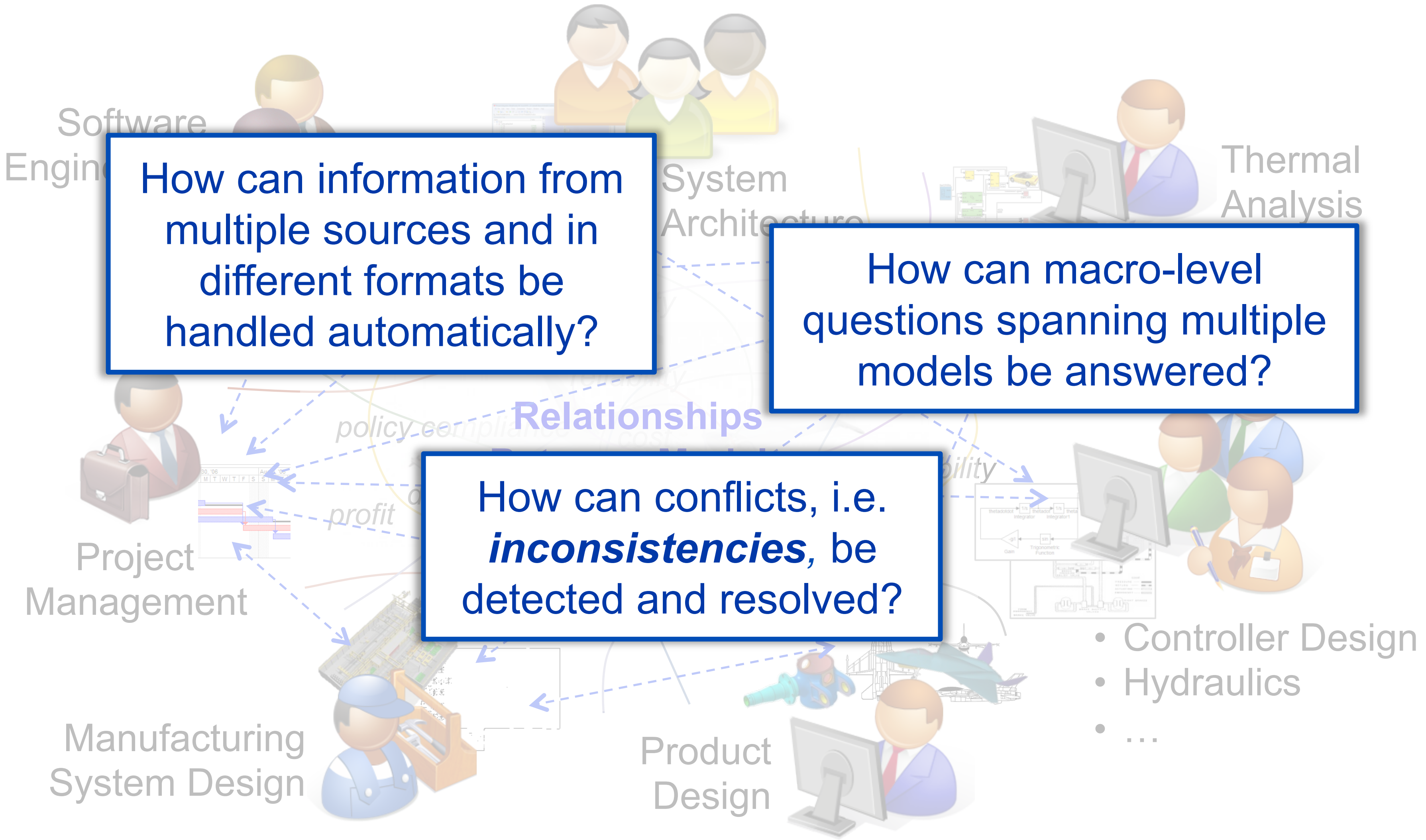
Relationships Between Models

Relationships Between Models



How can information from multiple sources and in different formats be handled automatically?

How can macro-level questions spanning multiple models be answered?

How can conflicts, i.e. ***inconsistencies***, be detected and resolved?

Overview

- Context & Motivation
- **How do we Think About Inconsistency Management?**
- Technology Demonstrator
- Current & Future Work
- Conclusions

What is an Inconsistency?

An inconsistency is a ***contradiction***

➔ There exists *no possible world* that can represent all of the given information

➔ Mathematically speaking, it is possible to derive a statement **S** and its negation **¬S**

Some more examples:

"The aircraft has 3 landing gears and the aircraft has 5 landing gears"
(logical contradiction)

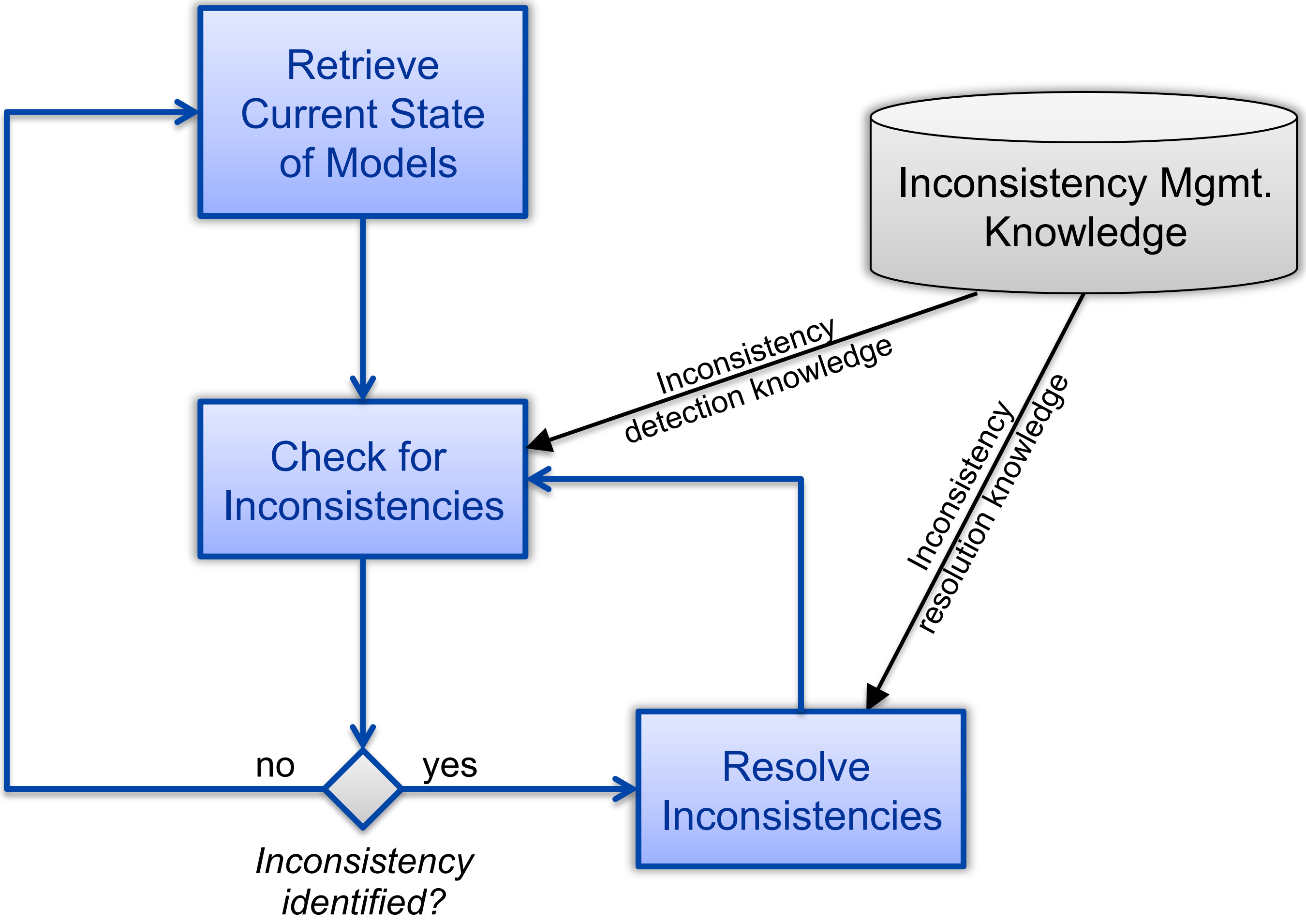
"On earth, the velocity of a free-falling object follows a sinusoidal curve"
(inconsistency w.r.t. observations and / or accepted theories / laws of nature)

"The probability of the engine failing is 0.1%, and I think it will not fail with a probability of 98%"
(mathematical inconsistency)

"I prefer apples over oranges, oranges over bananas, and bananas over apples"
(intransitive preferences)

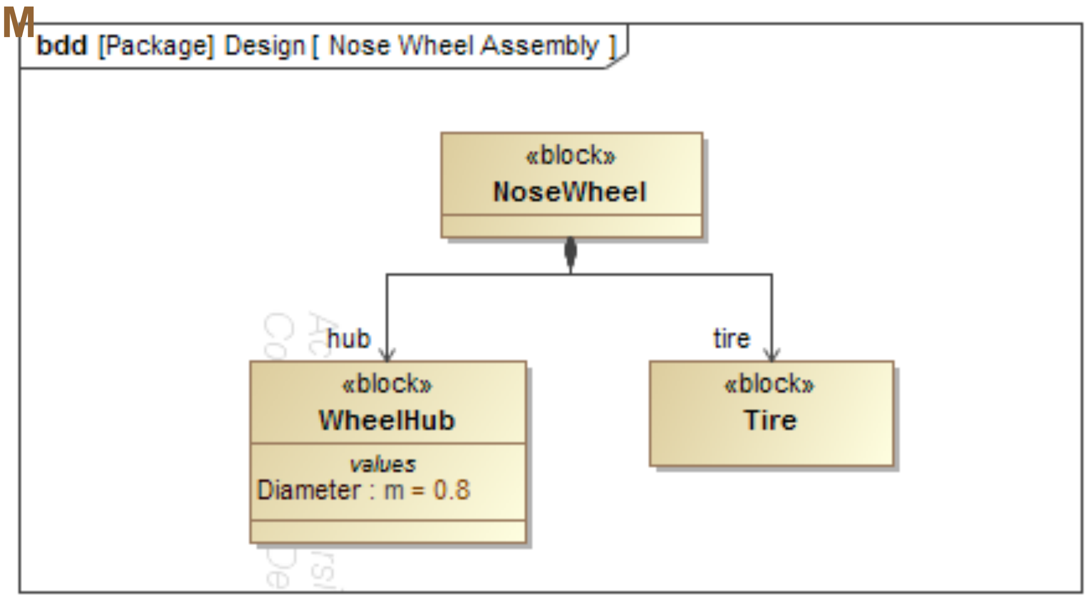
Mr. Spock (Star Trek) - Copyright (c) Paramount Pictures

A Basic Process for Inconsistency Management

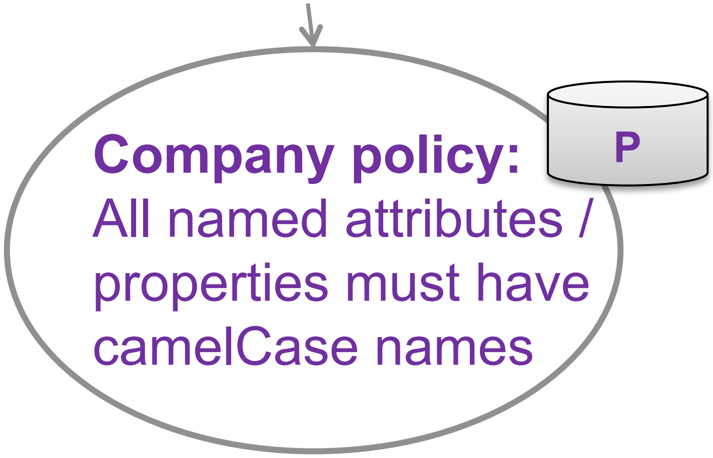

Retrieve Current State of Models
Check for Inconsistencies
Inconsistency Mgmt. Knowledge
Inconsistency detection knowledge
Inconsistency resolution knowledge
no
yes
Resolve Inconsistencies
Inconsistency identified?

Managing Inconsistencies – A Simple Example…

Evolve: add property with name “Diameter”



Inconsistency Mgmt. Knowledge



Company policy: All named attributes / properties must have camelCase names

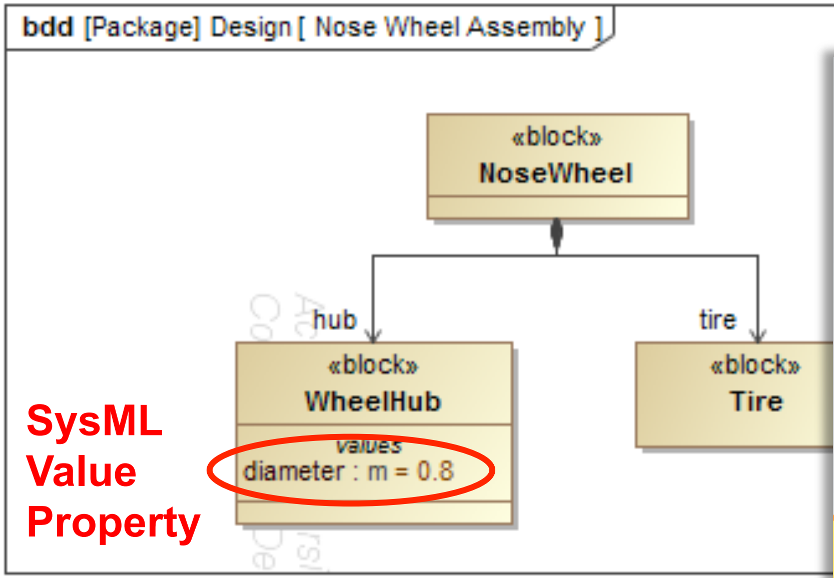
Does the model on the left violate this policy?

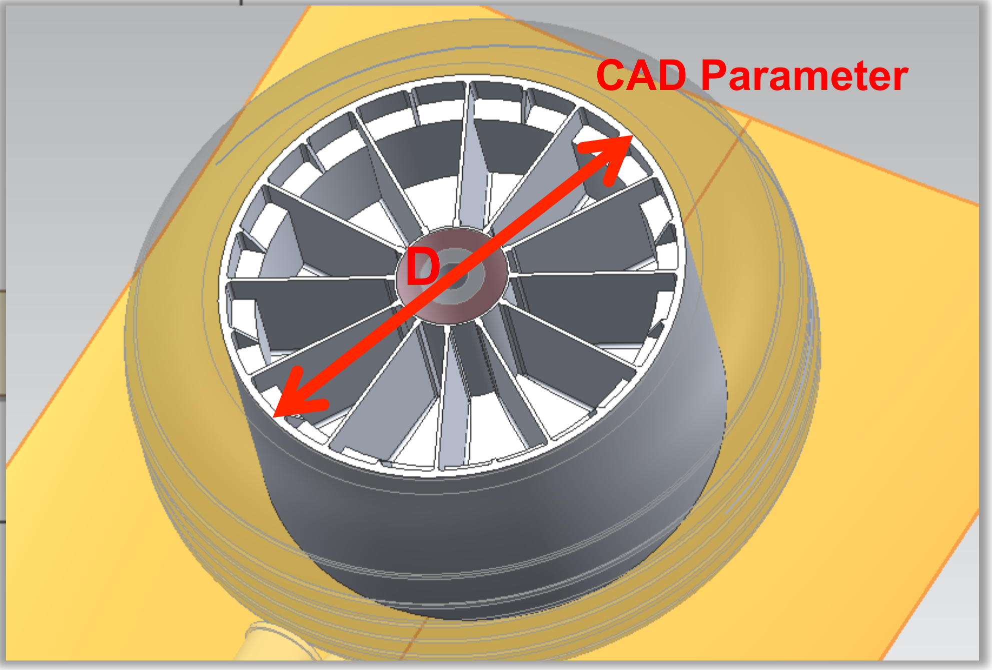
Check: the property's name is “Diameter” (**M**) ⇔ The property's name must be “diameter” (**P**)

- ➔ But, on a symbolic level, “diameter” and “Diameter” are distinctly different
- ➔ Hence, a contradiction exists - i.e., *inconsistency* can be derived fairly easily

Resolve: resolving is trivial in this case: change “Diameter” to “diameter” …

Example 2: Managing Inconsistencies Across Models

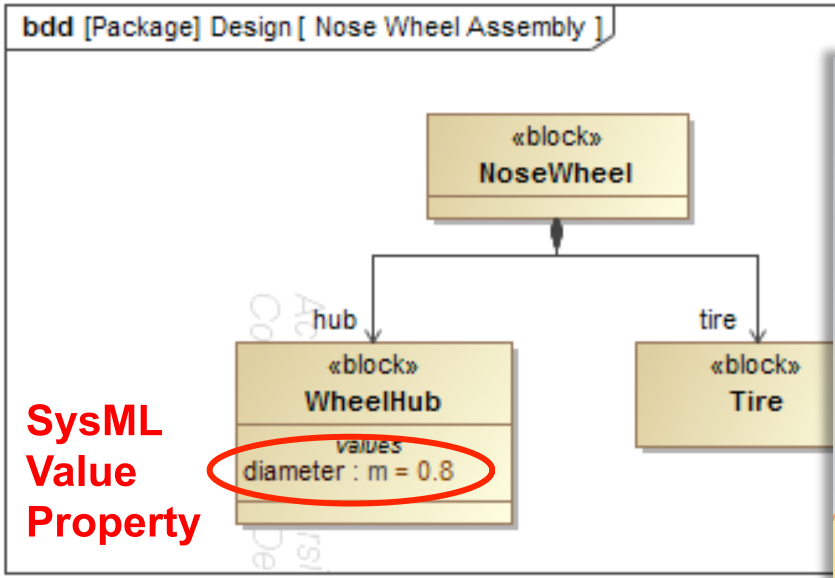




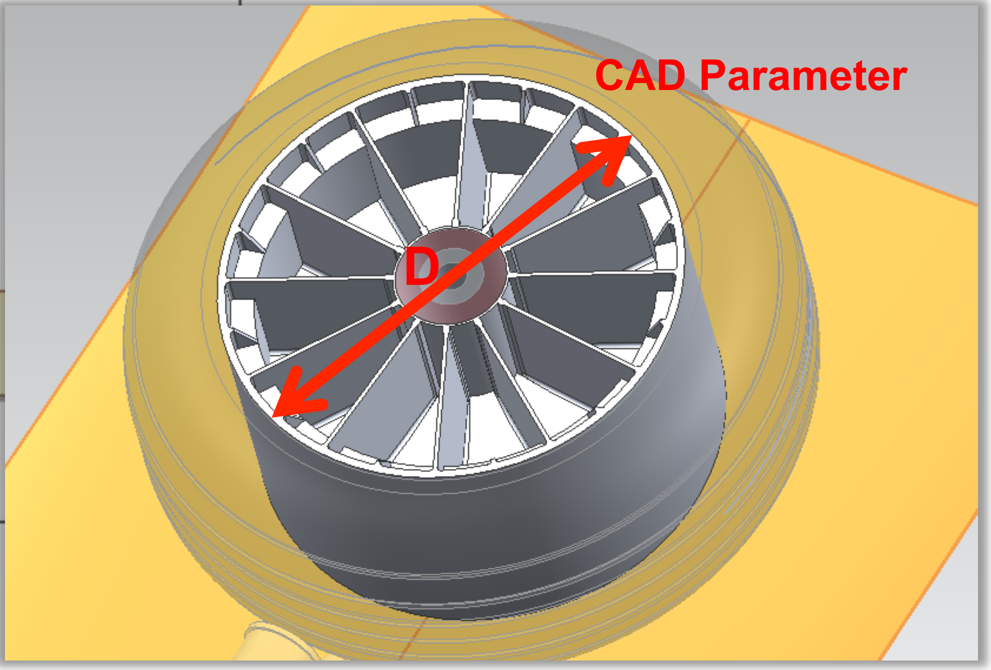
- Here, obvious overlap exists
  - A property / attribute is *semantically equivalent* ➔ a relation across models
  - Inconsistent if constraints on property are not compatible
- *Semantically equivalent properties with incompatible constraints are inconsistent* ➔ pattern can identify such inconsistencies

F86 Sabre CAD Data – Credit to ASDL, Georgia Tech

Example 2: Managing Inconsistencies Across Models



SysML Value Property



CAD Parameter

- Here, obvious overlap exists
  - A property / attribute is semantically equivalent ➔ a relation across models

1) How and where to capture relations across models?
2) How can patterns going across models be defined (and queried)?

➔ **Need a common representational formalism**

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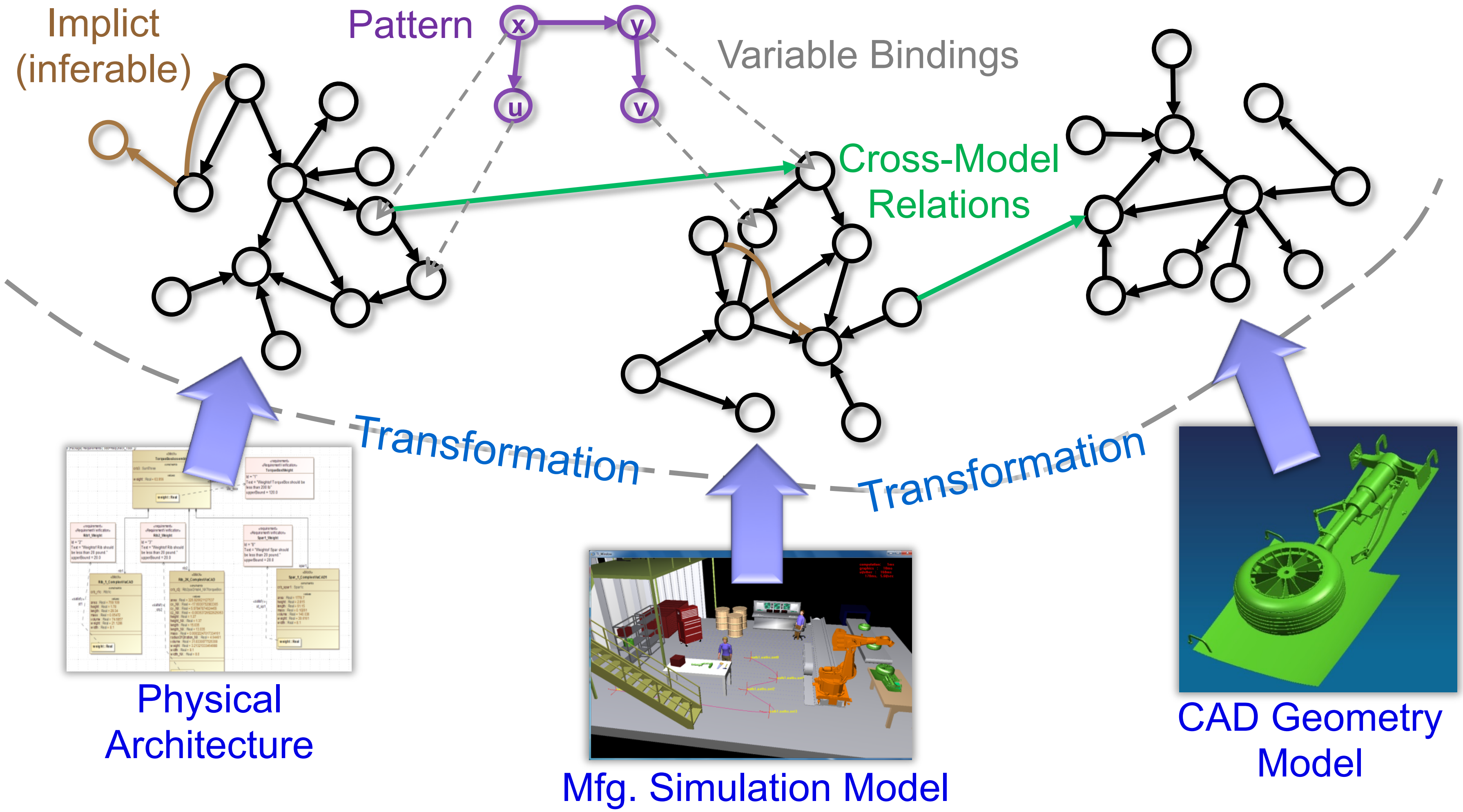
Graphs as a Common Representational Formalism



Implict (inferable)

Pattern

Variable Bindings

Cross-Model Relations

Transformation

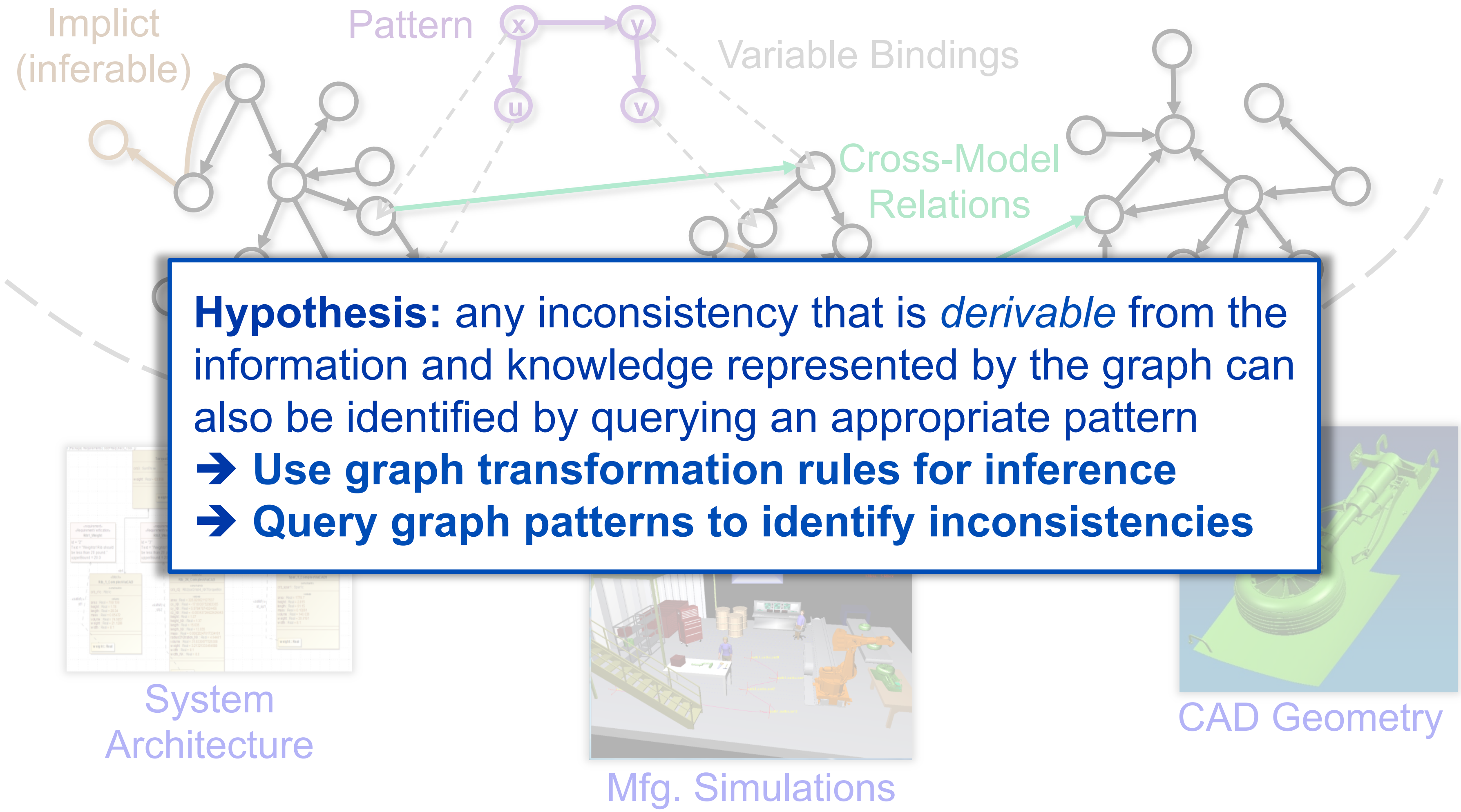
Transformation

Physical Architecture

Mfg. Simulation Model

CAD Geometry Model

Graphs as a Common Representational Formalism

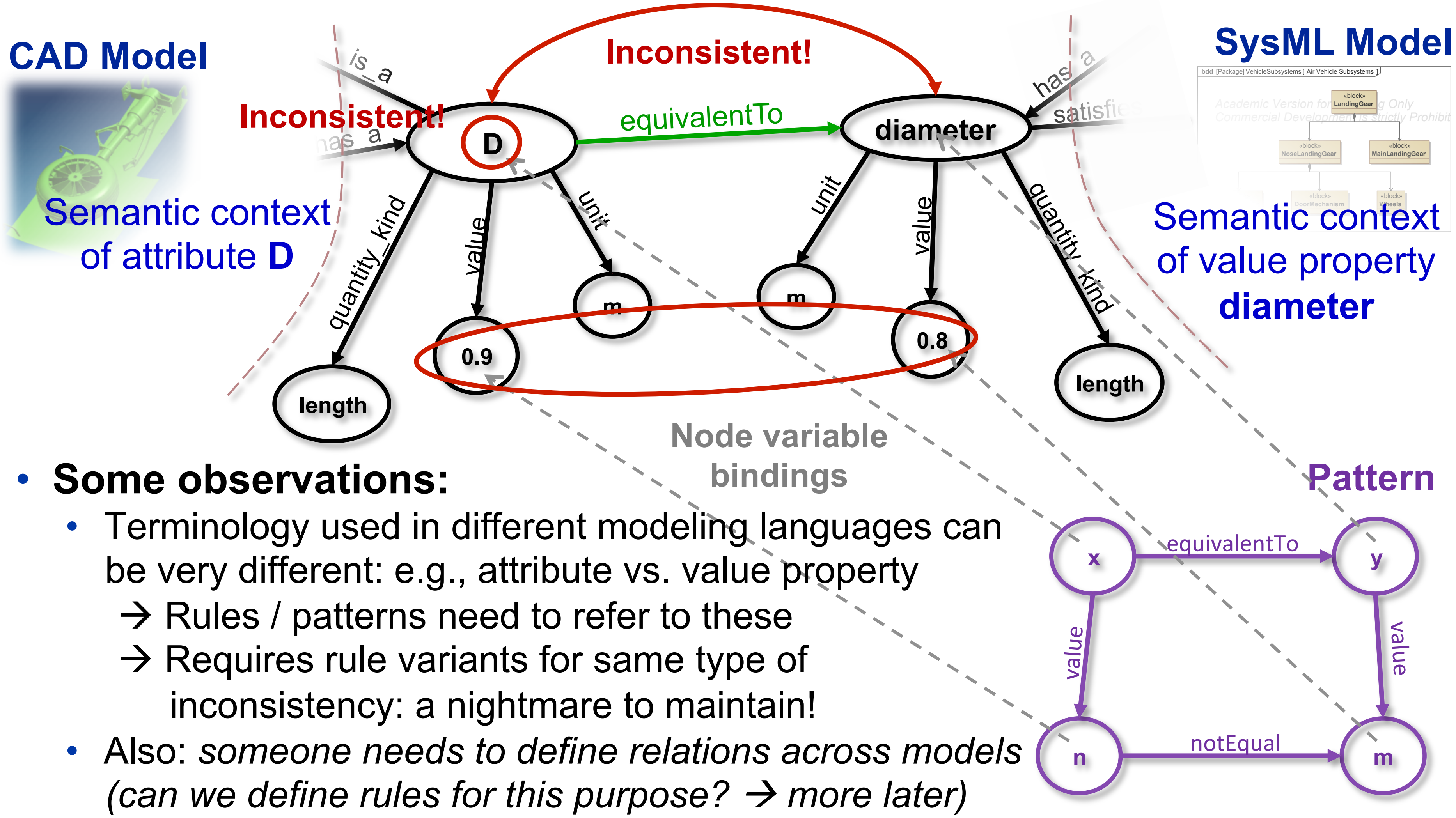


Hypothesis: any inconsistency that is *derivable* from the information and knowledge represented by the graph can also be identified by querying an appropriate pattern

➔ **Use graph transformation rules for inference**

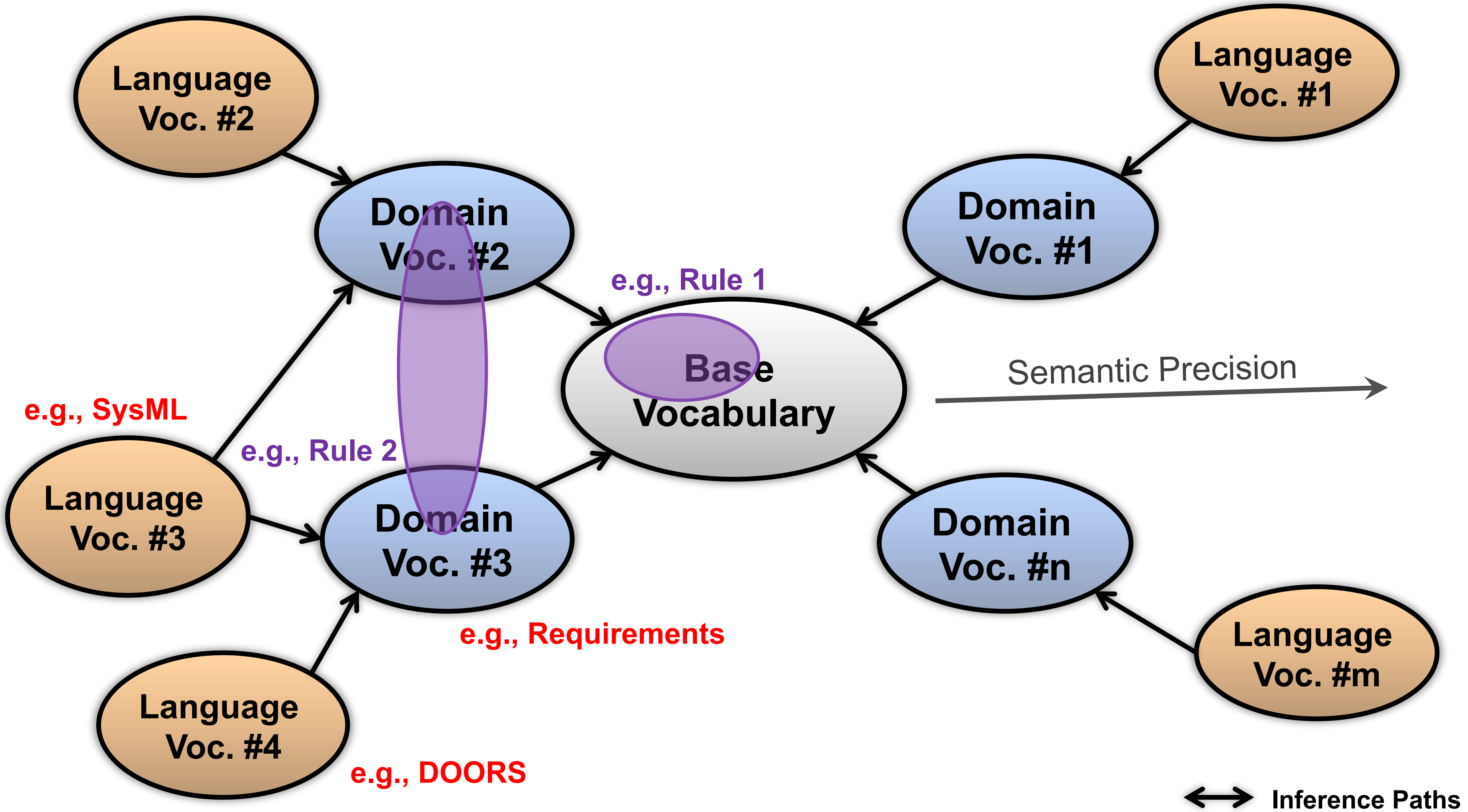
➔ **Query graph patterns to identify inconsistencies**

Identifying Inconsistencies by Querying Patterns



- **Some observations:**
  - Terminology used in different modeling languages can be very different: e.g., attribute vs. value property
    → Rules / patterns need to refer to these
    → Requires rule variants for same type of inconsistency: a nightmare to maintain!
  - Also: *someone needs to define relations across models (can we define rules for this purpose? → more later)*

Pattern Vocabulary - Varying Semantic Precision



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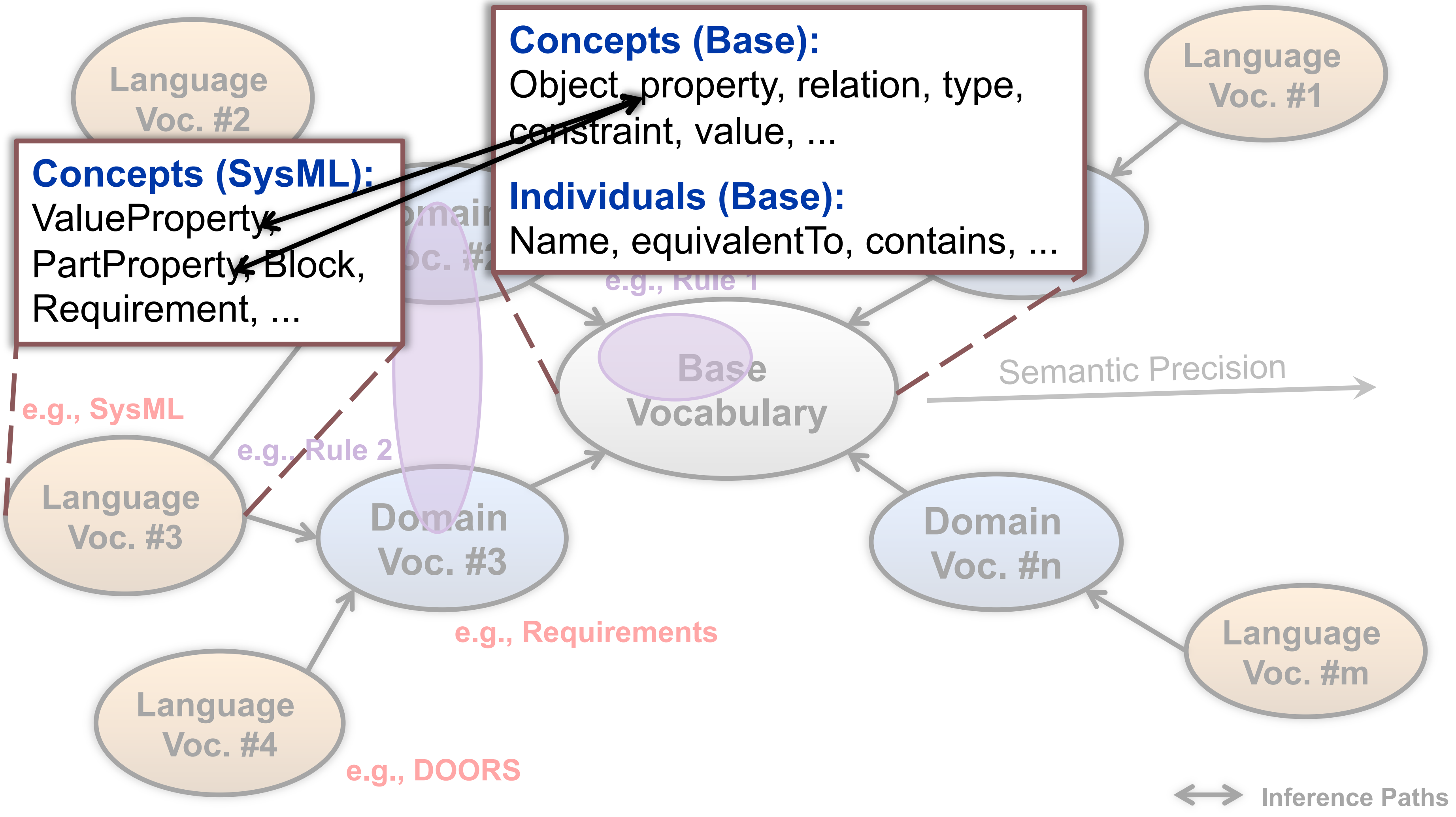

Concepts (SysML):
ValueProperty, PartProperty, Block, Requirement, ...

Concepts (Base):
Object, property, relation, type, constraint, value, ...

Individuals (Base):
Name, equivalentTo, contains, ...

Inconsistency Management

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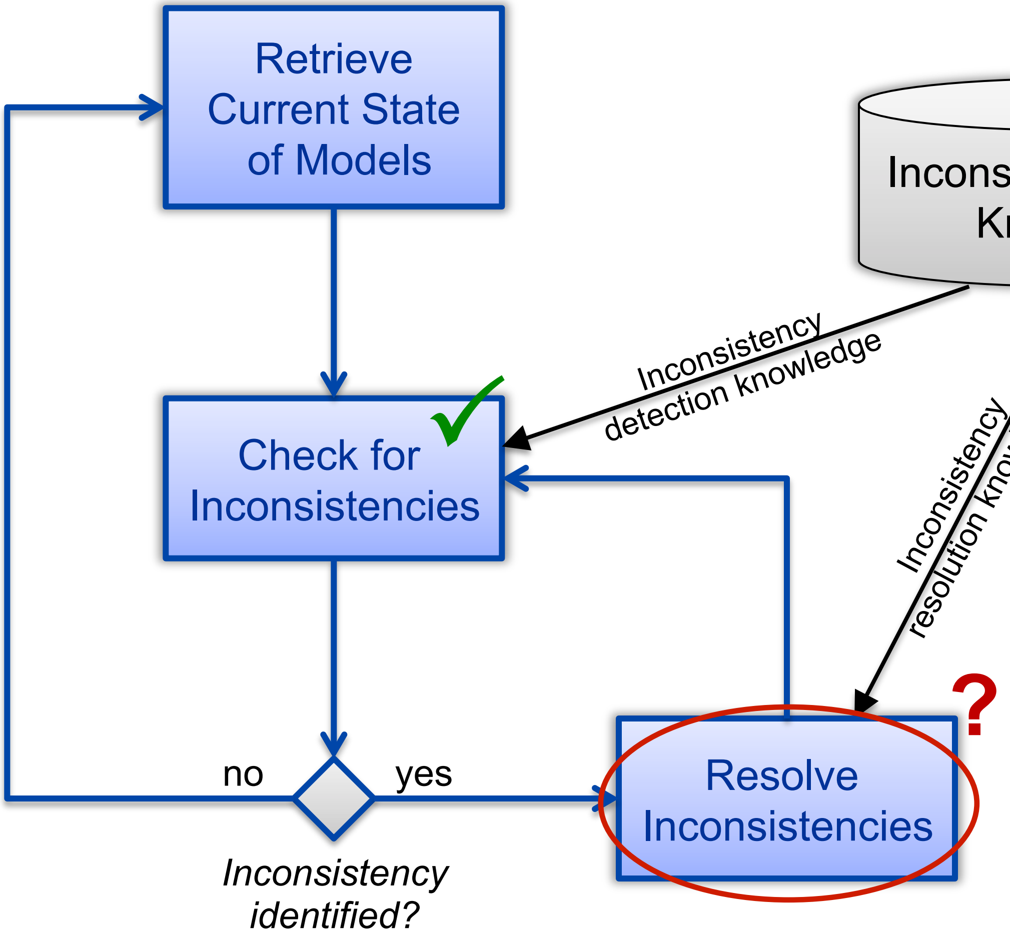

Retrieve Current State of Models
Inconsistency Mgmt. Knowledge
Inconsistency detection knowledge
Check for Inconsistencies
✓
Inconsistency resolution knowledge
no
yes
Resolve Inconsistencies
?
Inconsistency identified?

- ✓ Common representational formalism
- ✓ Manageable, unifying node & edge label vocabularies

How Do We Resolve These Inconsistencies?

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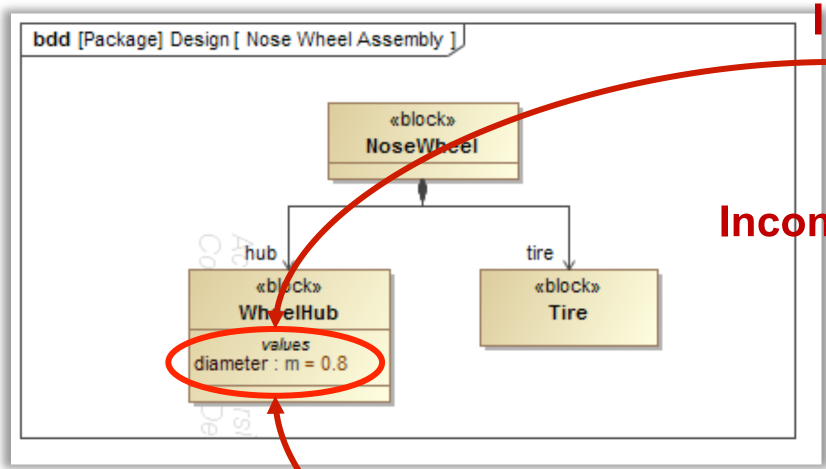
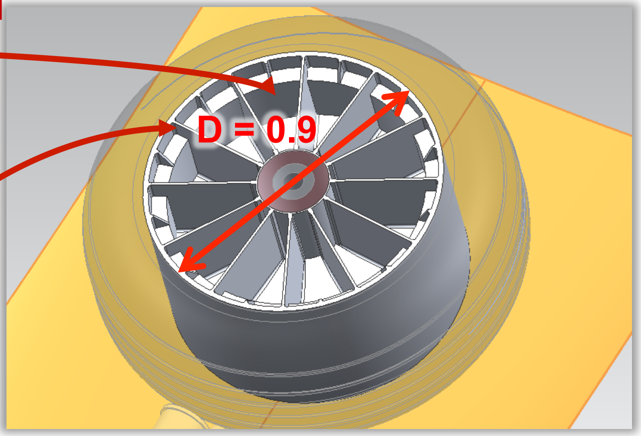
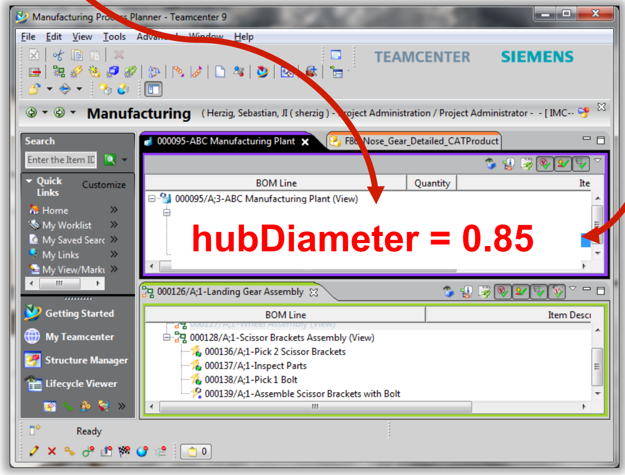


Inconsistency 1


D = 0.9

Inconsistency 3

Inconsistency 2


Manufacturing Process Planner - Teamcenter 9
File Edit View Tools Advanced Window Help
TEAMCENTER
SIEMENS
Manufacturing
(Herzig, Sebastian, JI (sherzig) - Project Administration / Project Administrator - - [IMC--
Search
Enter the Item ID
Quick Links
Customize
Home
My Worklist
My Saved Searc
My Links
My View/Mark
Getting Started
My Teamcenter
Structure Manager
Lifecycle Viewer
000095-ABC Manufacturing Plant
F8 Nose_Gear_Detailed_CATProduct
BOM Line
Quantity
Ite
000126/A;1-Landing Gear Assembly
BOM Line
Item Desc
Ready

000095/A;3-ABC Manufacturing Plant (View)

000127/A;1-Wheel Assembly (View)

000128/A;1-Scissor Brackets Assembly (View)

000136/A;1-Pick 2 Scissor Brackets

000137/A;1-Inspect Parts

000138/A;1-Pick 1 Bolt

000139/A;1-Assemble Scissor Brackets with Bolt

hubDiameter = 0.85

- Three different representations of the value for (semantically) the same property
- Can we resolve all of these inconsistencies automatically??

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Which Model Should We Trust?

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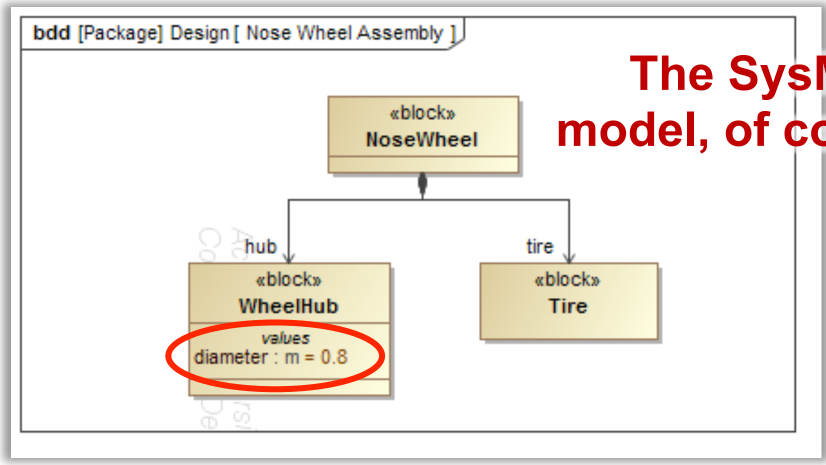
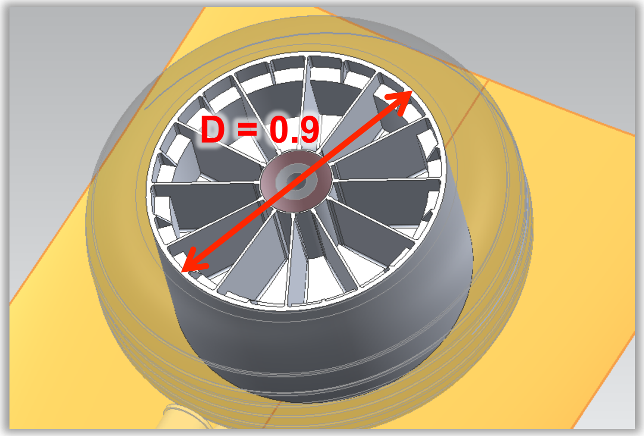
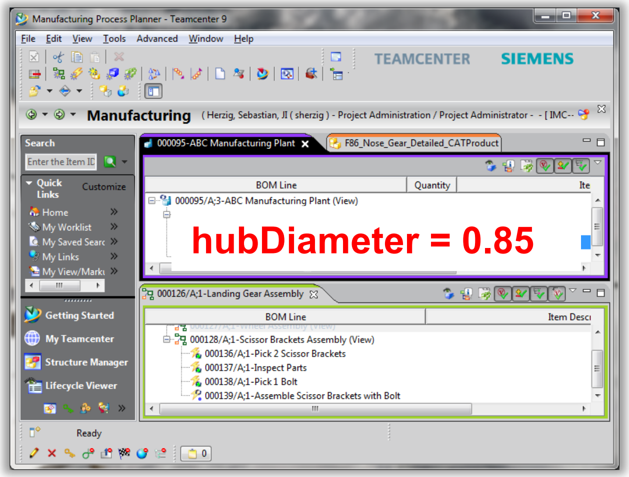


The SysML model, of course!



The information in the PLM / PDM system, of course!



Manufacturing (Herzig, Sebastian, JI (sherzig) - Project Administration / Project Administrator - - [IMC--

000095-ABC Manufacturing Plant | F86_Nose_Gear_Detailed_CATProduct

BOM Line	Quantity	Ite
000095/A;3-ABC Manufacturing Plant (View)		

hubDiameter = 0.85

000126/A;1-Landing Gear Assembly

BOM Line	Item Desci
000127/A;1-Wheel Assembly (View)	
000128/A;1-Scissor Brackets Assembly (View)	
000136/A;1-Pick 2 Scissor Brackets	
000137/A;1-Inspect Parts	
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Resolving Inconsistencies

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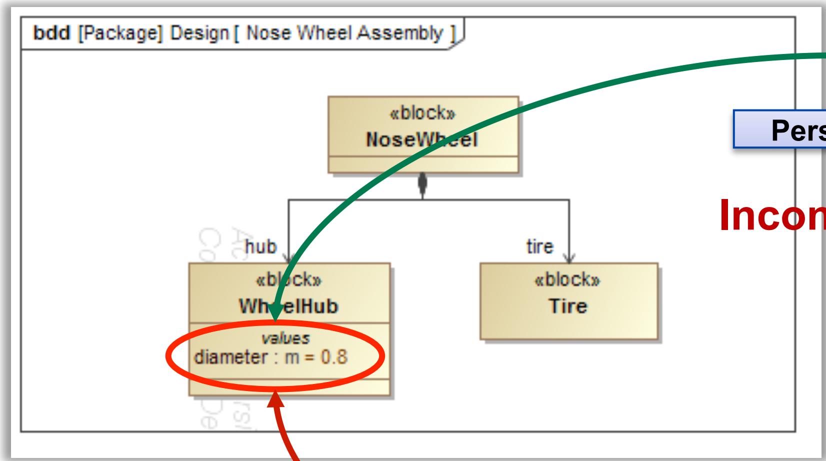
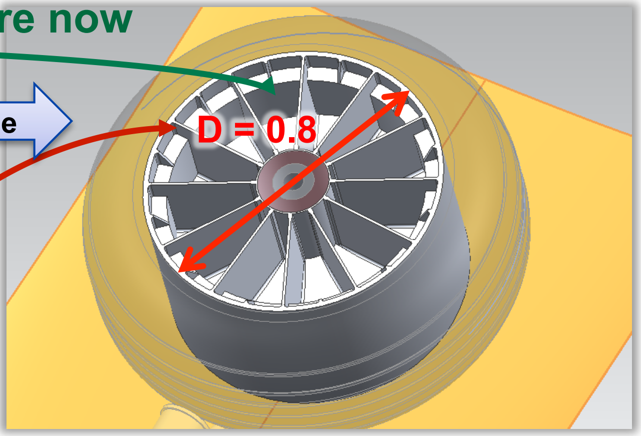


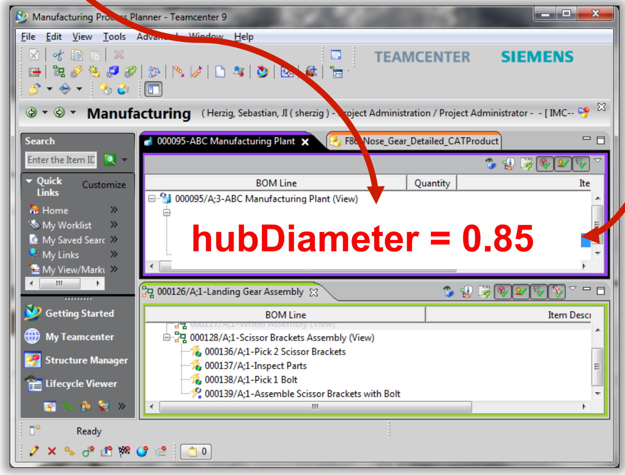
We're good here now

Person 1: Propagate Value

Inconsistency 3



Inconsistency 2



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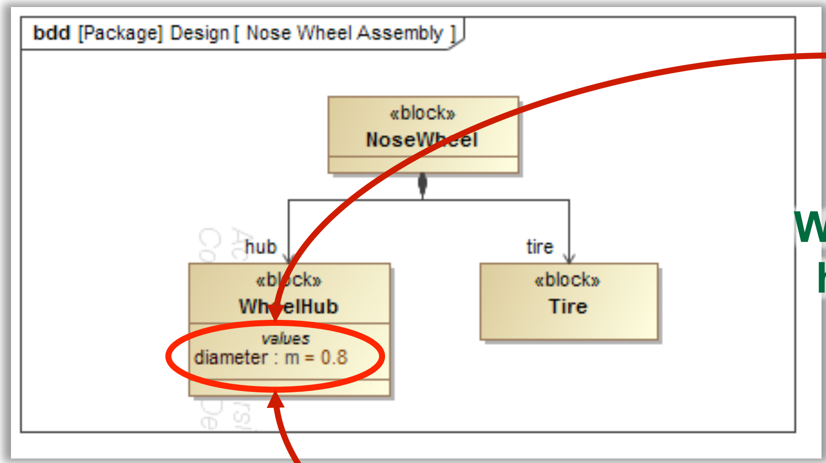
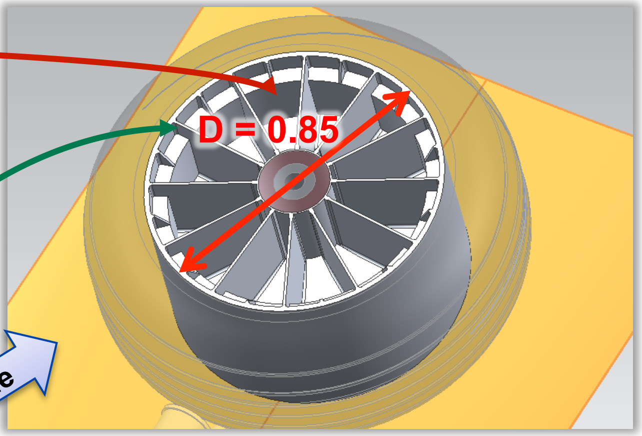
Resolving Inconsistencies



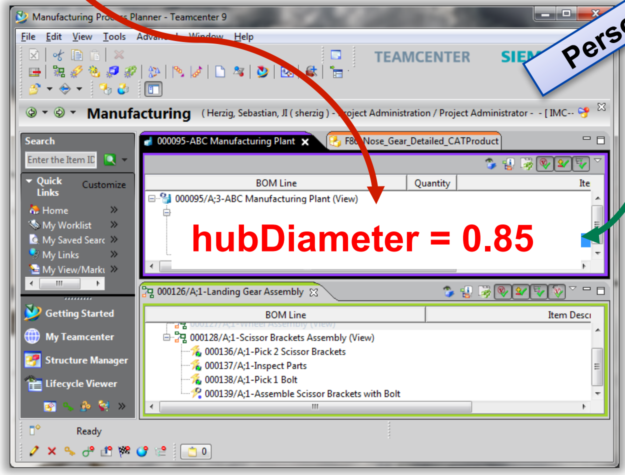
Oooops….



We're good here now

Inconsistency 2

Person 2: Propagate Value



Manufacturing (Herzig, Sebastian, JI (sherzig) - Project Administration / Project Administrator - - [IMC--

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BOM Line	Quantity	Ite
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Great, just negated our previous fix… why did this happen?

- ➔ Often more than one way to fix a particular (type of) inconsistency
- ➔ Multiple related inconsistencies
- ➔ Need some strategy to find optimal sequence of resolution actions: e.g., here, source of authority

Resolving Inconsistencies: a Decision-Making Problem

- Given:
  - Exhaustive list of possible fixes to particular kinds of inconsistencies
  - List of inconsistencies identified by a corresponding pattern
- We can use this information to generate a list of alternative sequences of fix operations
  - Some may lead to a better outcome than others ➔ Analyze
  - Which one of these is optimal depends on preferences and beliefs… ➔ Evaluate & select most preferable

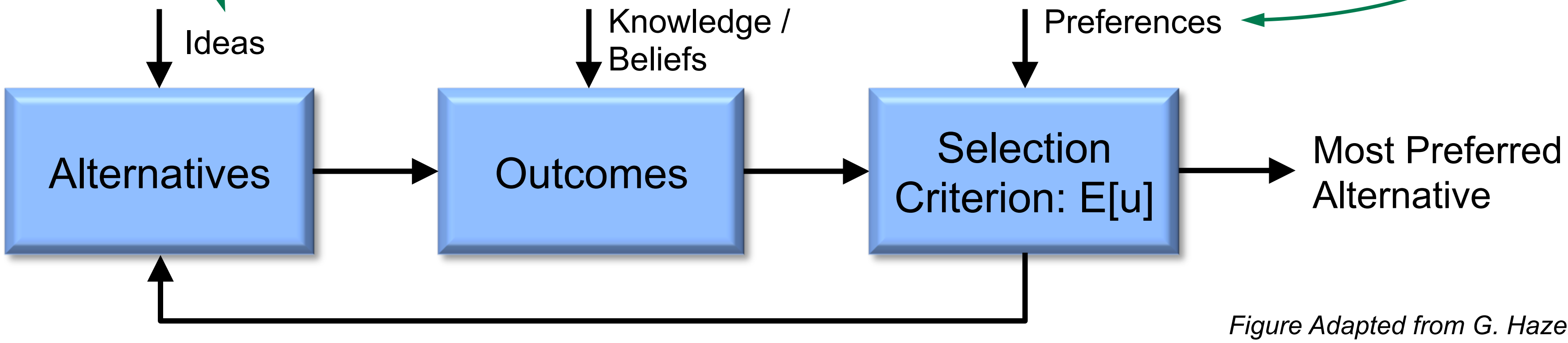
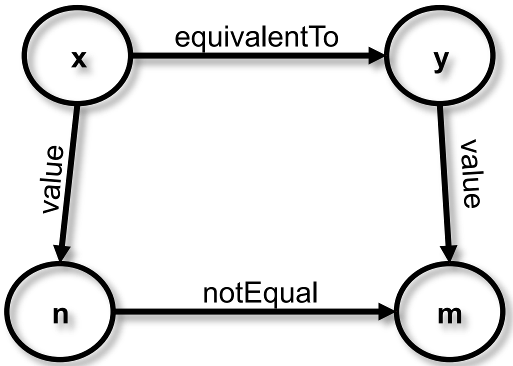
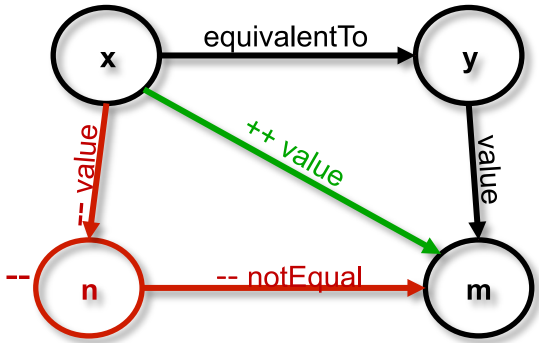


Figure Adapted from G. Hazelrigg

Summary: Makeup of an Inconsistency Rule

<table>
<tr><th>Identification Pattern & Context</th><th colspan="2">Resolution Alternatives</th></tr>
<tr><td rowspan="4">

<i>Applies:</i> always (invariant)
<i>Owner:</i> sherzig
<i>Created:</i> 2014-08-18
…</td><td>1</td><td>Tolerate / Do Nothing</td></tr>
<tr><td>2</td><td>
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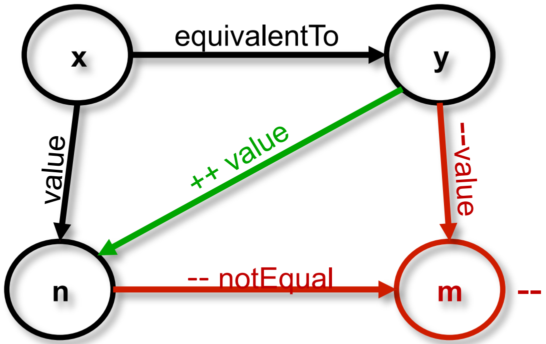
<tr><td>3</td><td>
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<tr><td>w</td><td>…</td></tr>
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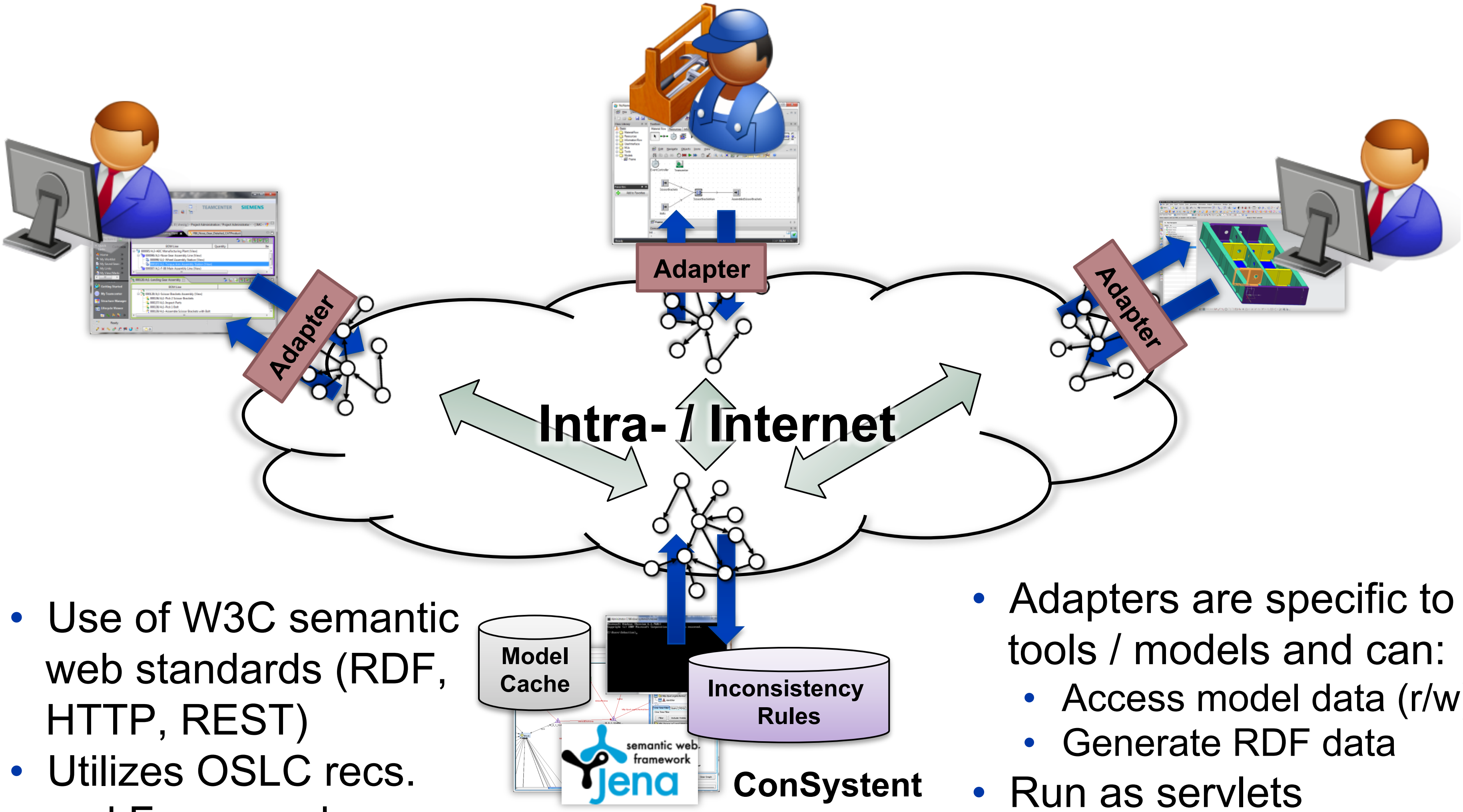
Overview

- Context & Motivation
- How do we Think About Inconsistency Management?
- **Technology Demonstrator**
- Current & Future Work
- Conclusions

Technology Demonstrator: ConSystent

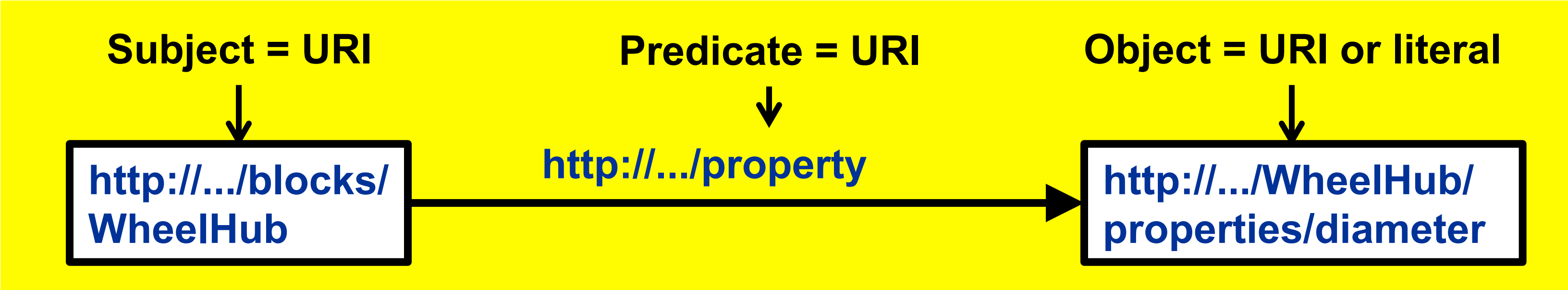


- Use of W3C semantic web standards (RDF, HTTP, REST)
- Utilizes OSLC recs. and Framework

- Adapters are specific to tools / models and can:
  - Access model data (r/w)
  - Generate RDF data
- Run as servlets

Resource Description Framework (RDF)

- Statements about resources in the form of subject-predicate-object expressions (triples) ➔ put together, these form a graph



Subject = URI

Predicate = URI

Object = URI or literal

http://.../blocks/WheelHub

http://.../property

http://.../WheelHub/properties/diameter

- World Wide Web Consortium (W3C) standard for data interchange
- Used in Semantic Web applications → stronger semantics for websites, enabling next generation search engines
- Variety of syntax notations and data serialization formats (e.g., XML)

Adapted and Used with Permission from Axel Reichwein, Koneksys LLC

Open Services for Lifecycle Collaboration (OSLC)

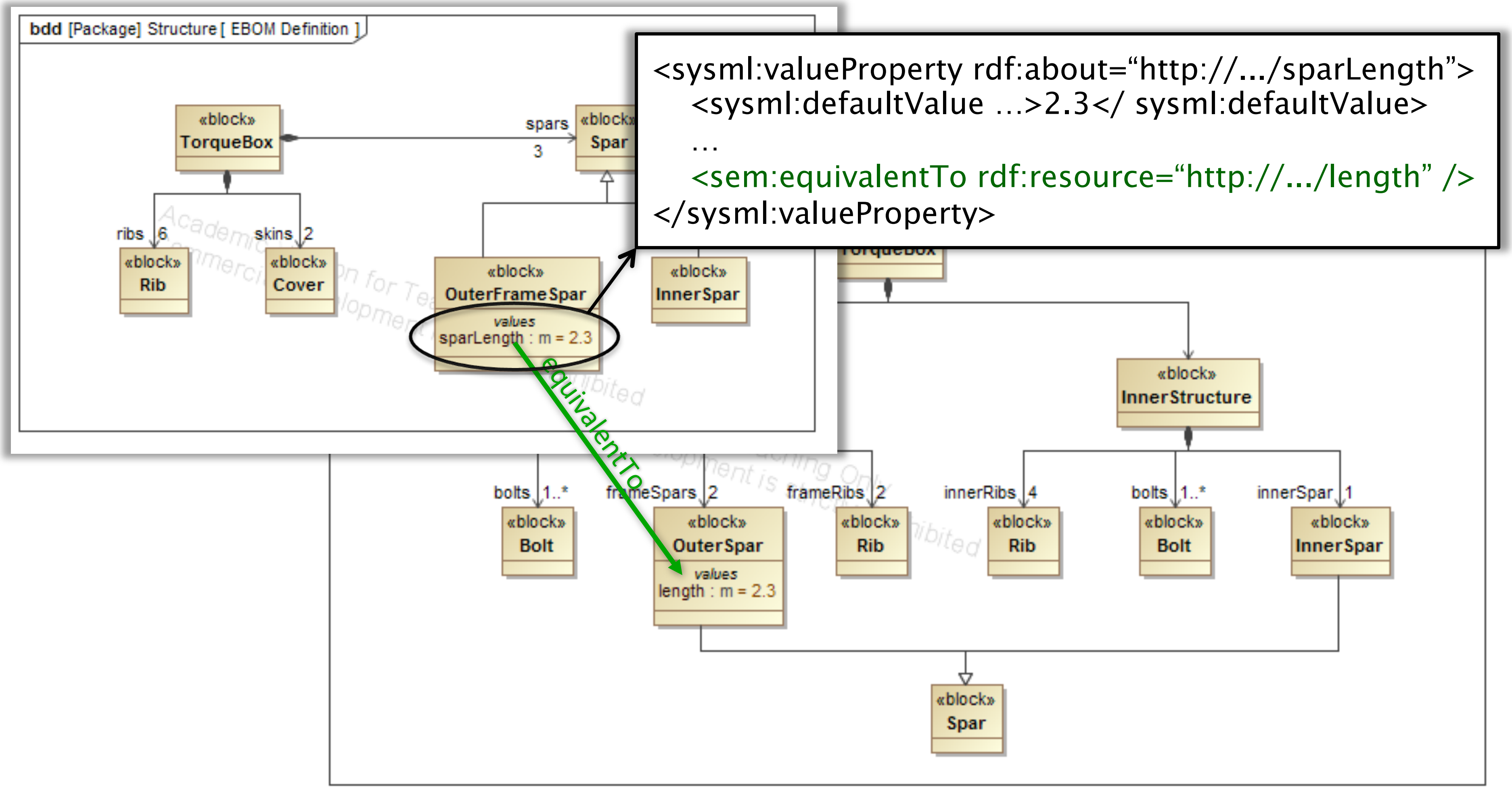
- OSLC adds additional semantics for expressing structural constraints on RDF data (e.g., cardinality)
- Domain vocabularies introduce standard terminology across domains

OSLC Core Vocabulary **+**

Domain / Language Vocabularies	Status
ALM/PLM Interoperabiltiy	Draft
Architecture Management	2.0
Asset Management	2.0
Automation	2.0
Change Management	2.0
Estimation and Measurement	Draft
Performance Monitoring	2.0
Quality Management	2.0
Reconciliation	2.0
Requirements Management	2.0
MBSE / SysML	Draft

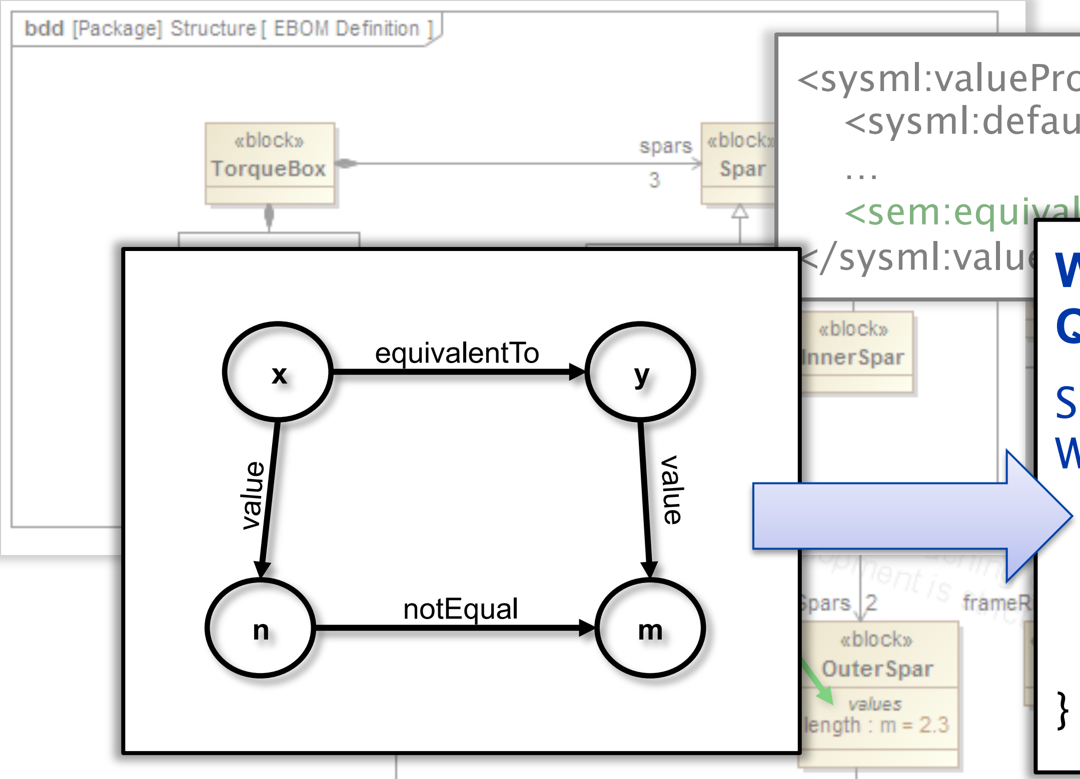
OSLC resource types for various domains and languages

Example - Inconsistency Detection



```
<sysml:valueProperty rdf:about="http://.../sparLength">
   <sysml:defaultValue …>2.3</ sysml:defaultValue>
   …
   <sem:equivalentTo rdf:resource="http://.../length" />
</sysml:valueProperty>
```

Example - Inconsistency Detection



```
<sysml:valueProperty rdf:about=“http://.../sparLength”>
   <sysml:defaultValue …>2.3</ sysml:defaultValue>
   …
   <sem:equivalentTo rdf:resource=“http://.../length” />
</sysml:value
```

W3C Standard for Querying RDF: SPARQL

```
SELECT ?x ?y
WHERE  {
    ?x :equivalentTo ?y .
    ?x :value ?n .
    ?y :value ?m .
    FILTER(?n != ?m)
}
```

Inconsistency patterns (and, generally, inconsistency rules) are represented in a language such as SPARQL and executed using a corresponding engine

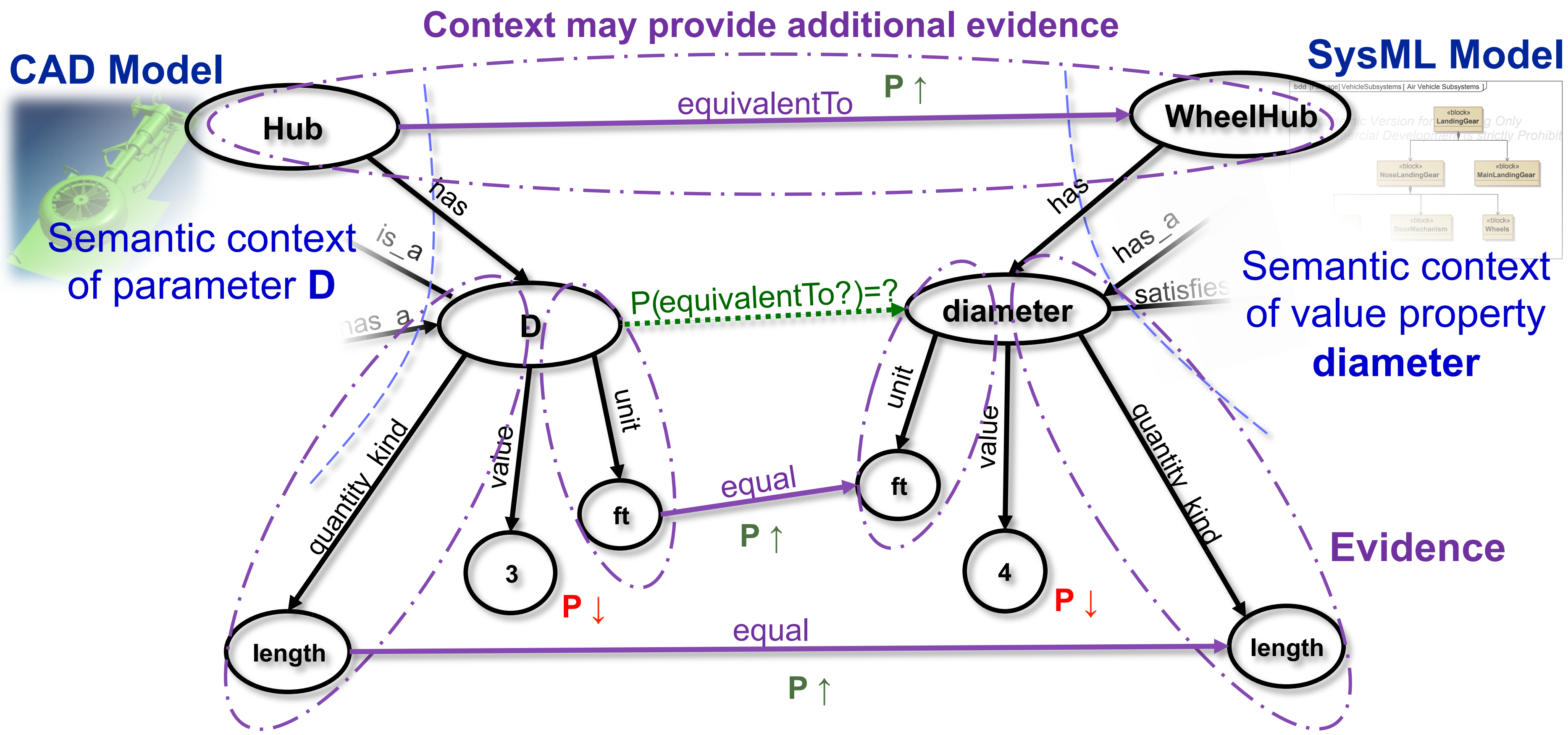
Status of OSLC Adapters Developed @ MBSEC

- **Open Source**
  - **NoMagic MagicDraw SysML (now / soon part of Eclipse Lyo)**
  - **Mathworks Simulink (now / soon part of Eclipse Lyo)**
- **Have also developed adapters for:**
  - **PTC Integrity (Requirements Management)**
  - **LMS Imagine Lab AMESim (Multi-Domain Systems Simulation)**
- **Examples of adapters developed outside of MBSEC:**
  - **Siemens Teamcenter (General Motors)**
  - **Bugzilla (part of Eclipse Lyo)**
  - **NinaCRM**
  - **…**

Overview

- Context & Motivation
- How do we Think About Inconsistency Management?
- Technology Demonstrator
- **Current & Future Work**
- Conclusions

Current Work – Probabilistic Inconsistency Reasoning



Context may provide additional evidence

CAD Model

SysML Model

Semantic context of parameter **D**

Semantic context of value property **diameter**

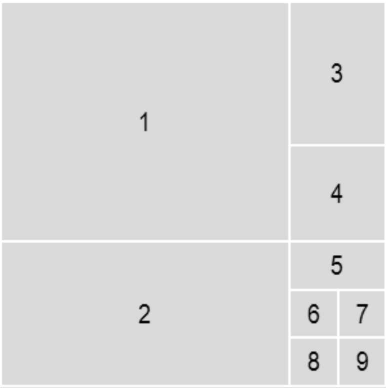
Evidence

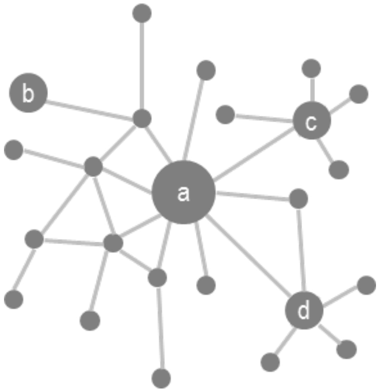
Prior Belief + Identified Features (“Evidence”) = Updated Belief

… and in the same spirit: P(Inconsistent) = ?

Future Work – Visualization

- Visual analytics tools to generate interactive visualizations using data from various system modeling sources
- Explore global patterns in data
- Seamless transition between models from various domains

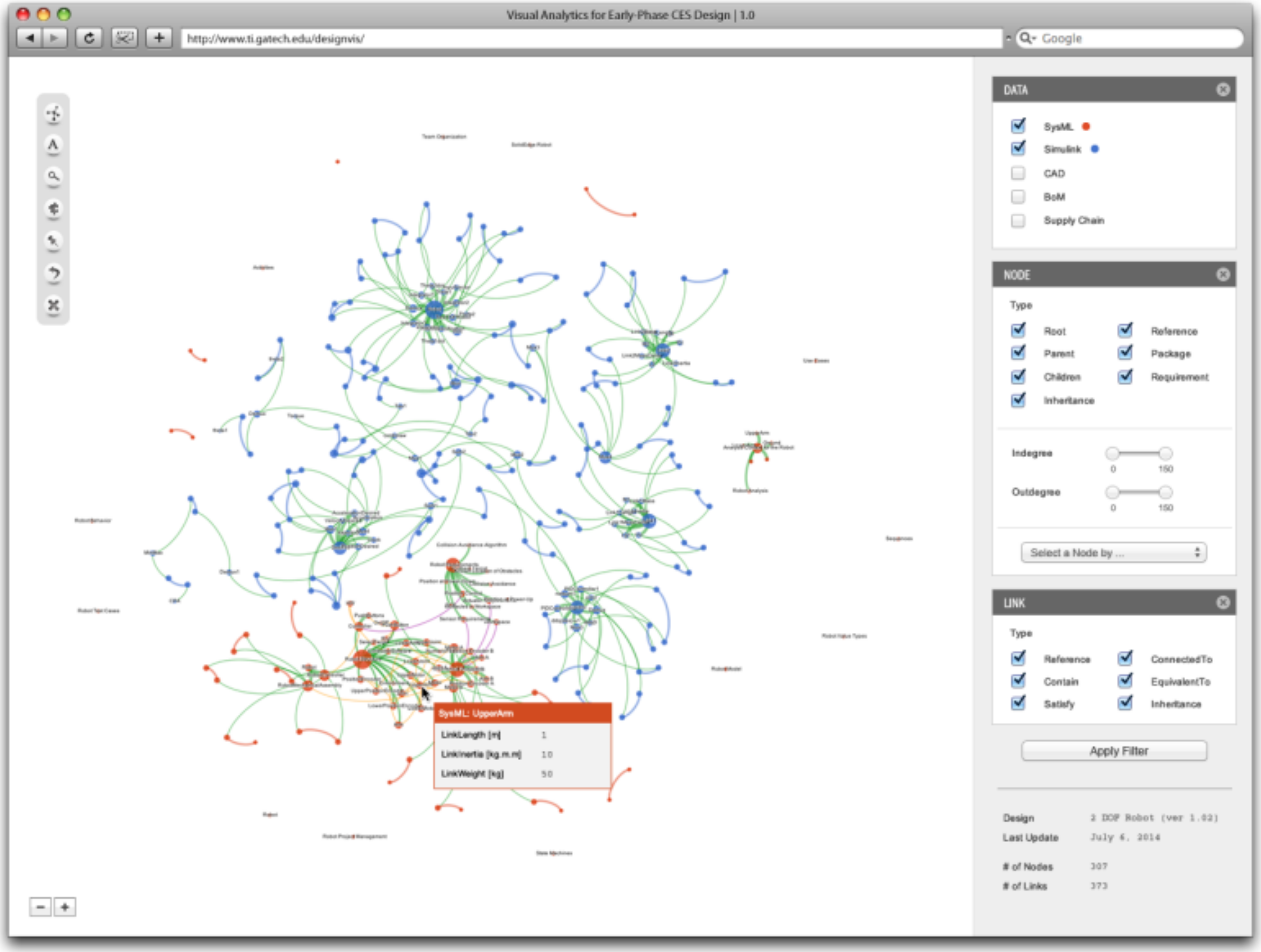




Future work with Dr. Rahul Basole (CS), Dr. Leon McGinnis (ISyE)

Future Work – Visualization

- Visua ations
  using
- Explo
- Sear mains



Visual Analytics for Early-Phase CES Design | 1.0
http://www.ti.gatech.edu/designvis/
Google

DATA

- ☑ SysML ●
- ☑ Simulink ●
- □ CAD
- □ BoM
- □ Supply Chain

NODE

Type

- ☑ Root
- ☑ Parent
- ☑ Children
- ☑ Inheritance
- ☑ Reference
- ☑ Package
- ☑ Requirement

Indegree 0 150

Outdegree 0 150

Select a Node by ...

LINK

Type

- ☑ Reference
- ☑ Contain
- ☑ Satisfy
- ☑ ConnectedTo
- ☑ EquivalentTo
- ☑ Inheritance

Apply Filter

Design	2 DOF Robot (ver 1.02)
Last Update	July 6, 2014
# of Nodes	307
# of Links	373

SysML: UpperArm

LinkLength [m]	1
LinkInertia [kg.m.m]	10
LinkWeight [kg]	50

Future work with Dr. Rahul Basole (CS), Dr. Leon McGinnis (ISyE)

Conclusions & Key Takeaways

- Inconsistency management = continuous V&V
- Directed, attributed, typed multi-graphs can be used to represent a wide variety of engineering models
- Graph patterns can be used to model types of inconsistencies and query for these
- Resolving inconsistencies is a decision-making problem, where the most preferred alternative sequence of "fix" operations must be determined
- Semantic web technologies are a powerful and practical basis for a scalable model integration framework

Backup Slides

GLOBAL PRODUCT DATA INTEROPERABILITY

SUMMIT

2014

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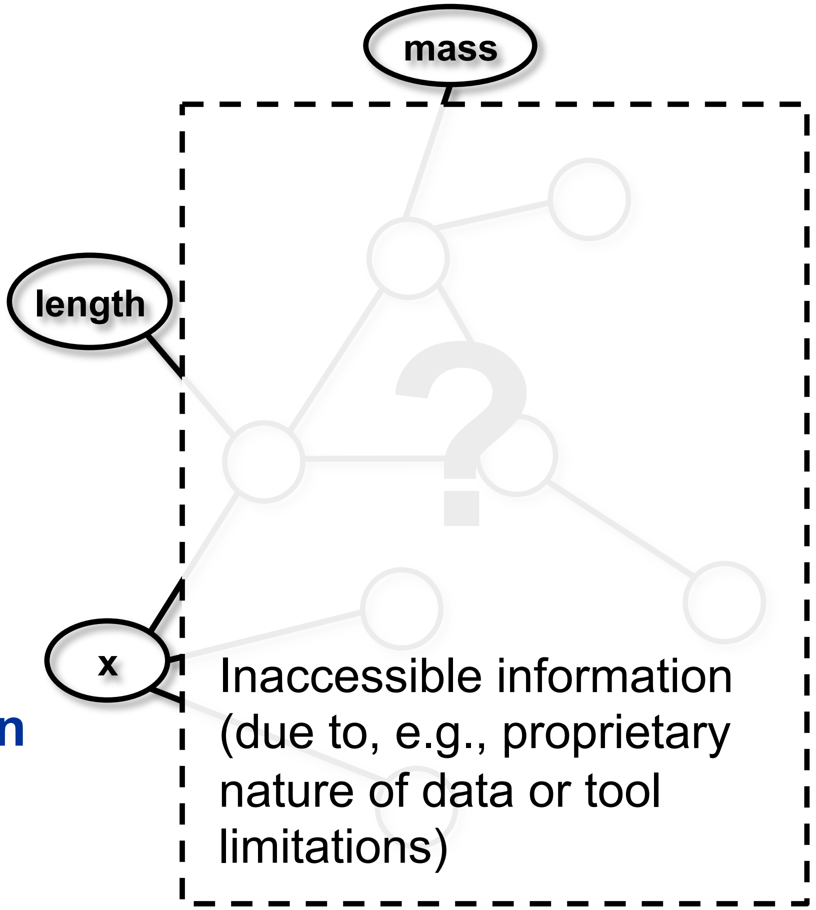
Some Open Questions…

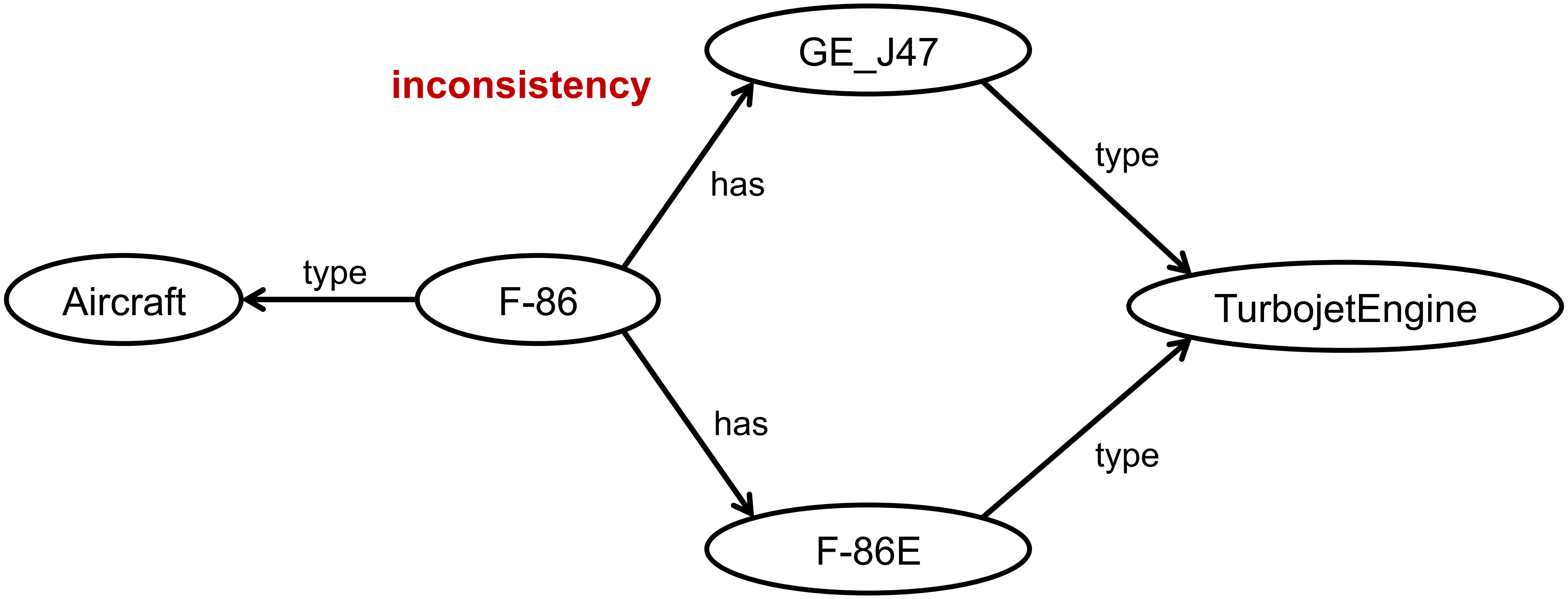
- **Access Control**
  - **Who can access which (select parts of) models, and with which rights?**
  - **How do we deal with restricted access to some data (e.g., ITAR)?**
- **Rule & Inter-Model Relations Ownership**
  - **Who manages the rules for which portion of the system?**
  - **Who should manage relations between models?**
- **Automated Inconsistency Resolution**
  - **Is it ever a good idea to autonomously resolve an inconsistency?**



Inaccessible information (due to, e.g., proprietary nature of data or tool limitations)

Reasoning About Inconsistencies

- **Assume the following axiom holds in our world (verbally):**
  - **"Any Aircraft has exactly one kind of Turbojet Engine"**



Associated Formal Reasoning Process

- **An inconsistency exists if we can deduce that (in our world) there exists an *Aircraft* that has two (different) types of *TurbojetEngines***
- **Facts explicitly and *implicitly* encoded in graph:**
  - **“F-86 type Aircraft”**
  - **“GE_J47 type TurbojetEngine”**
  - **“F-86E type TurbojetEngine”**
  - **“GE_J47 differentFrom F-86E”**
  - **“F-86 has GE_J47”**
  - **“F-86 has F-86E”**
  - **“F-86 has two TurbojetEngines”**

Deduced from CWA or specified under OWA

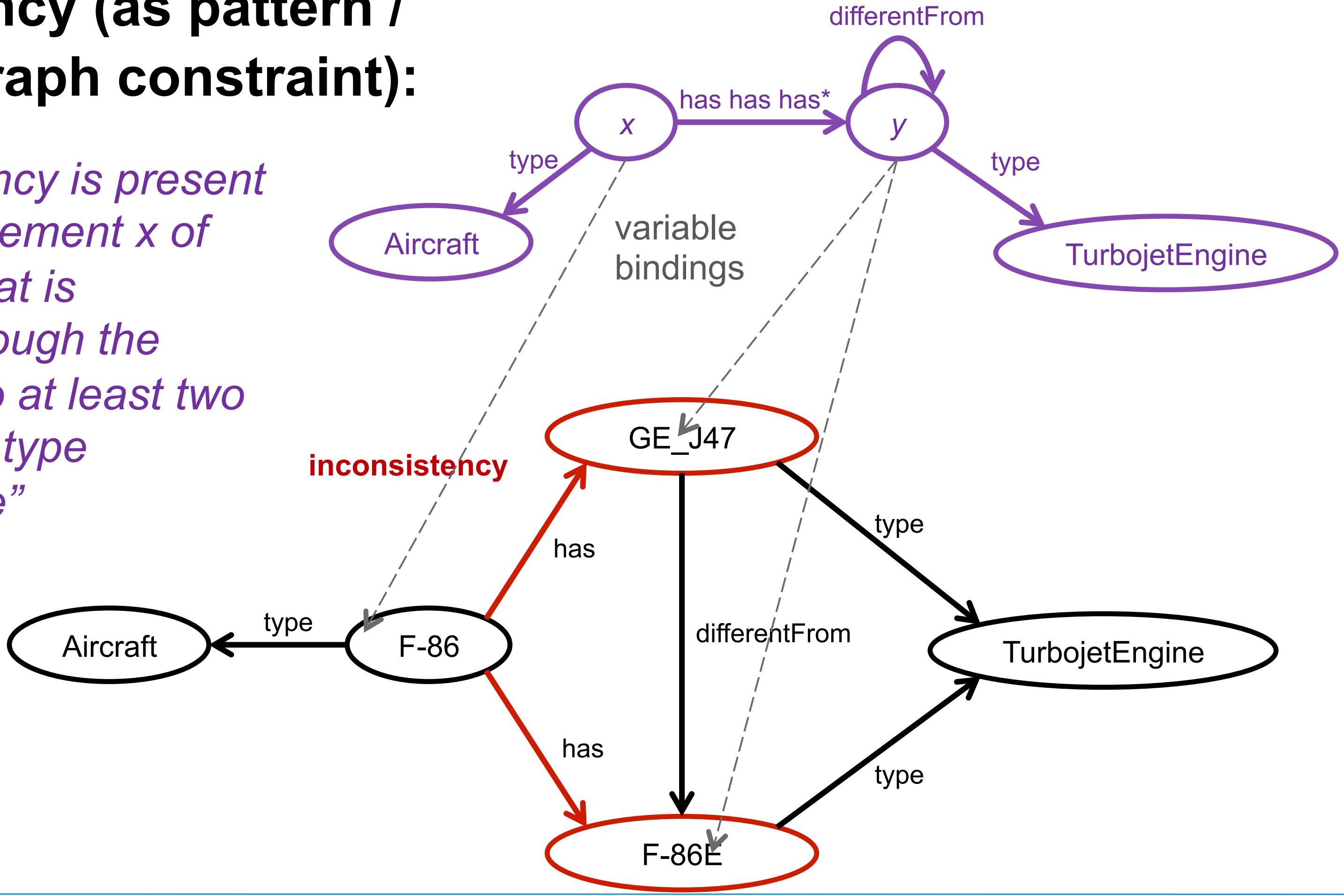
Derived fact from previous two statements

Inconsistent, because:
(F-86 has two TurbojetEngines) ∧ (F-86 has one Turbojet Engine) ⇒ ⊥

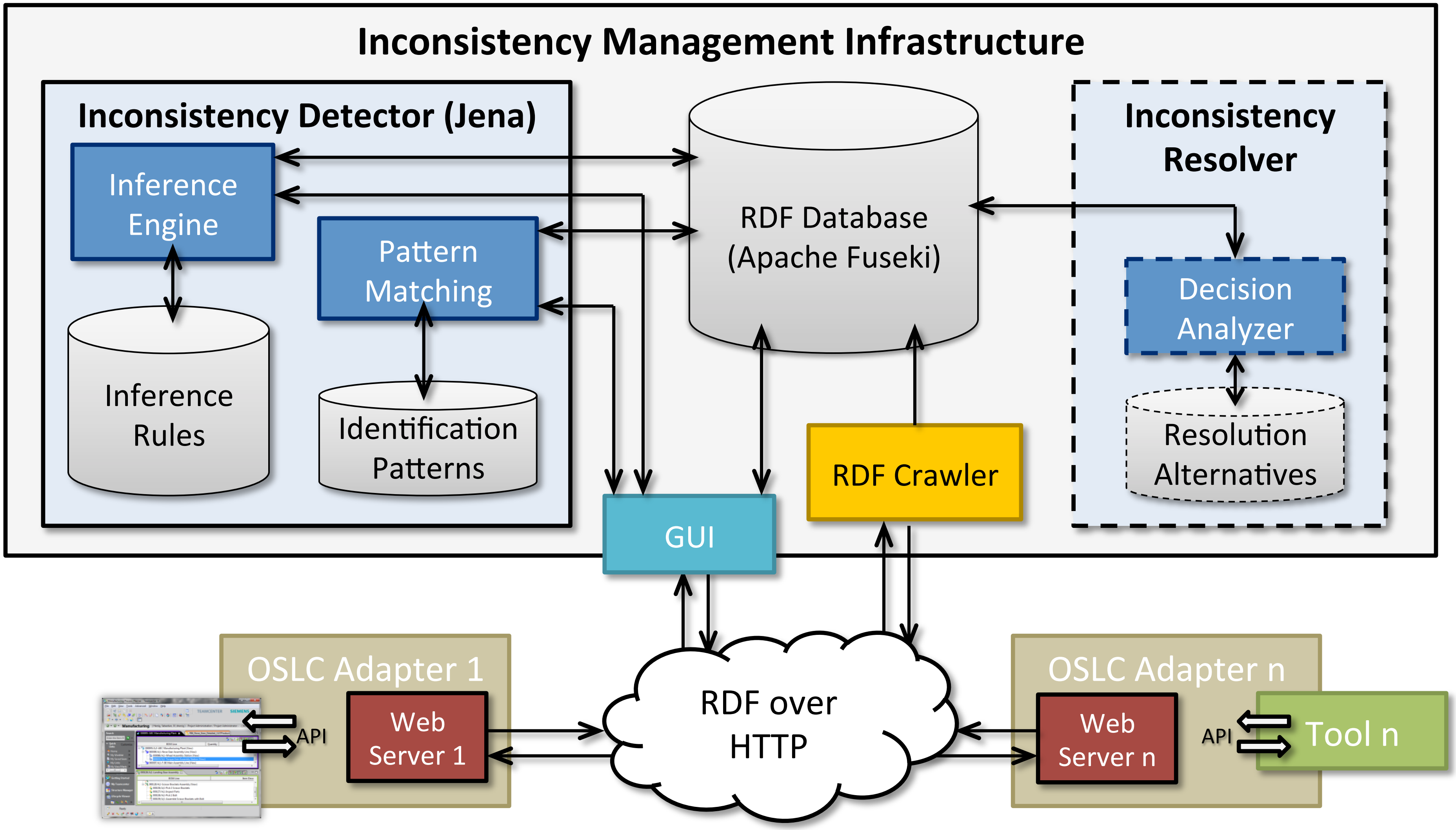
Pattern for Previous Example

- **Inconsistency (as pattern / negative graph constraint):**

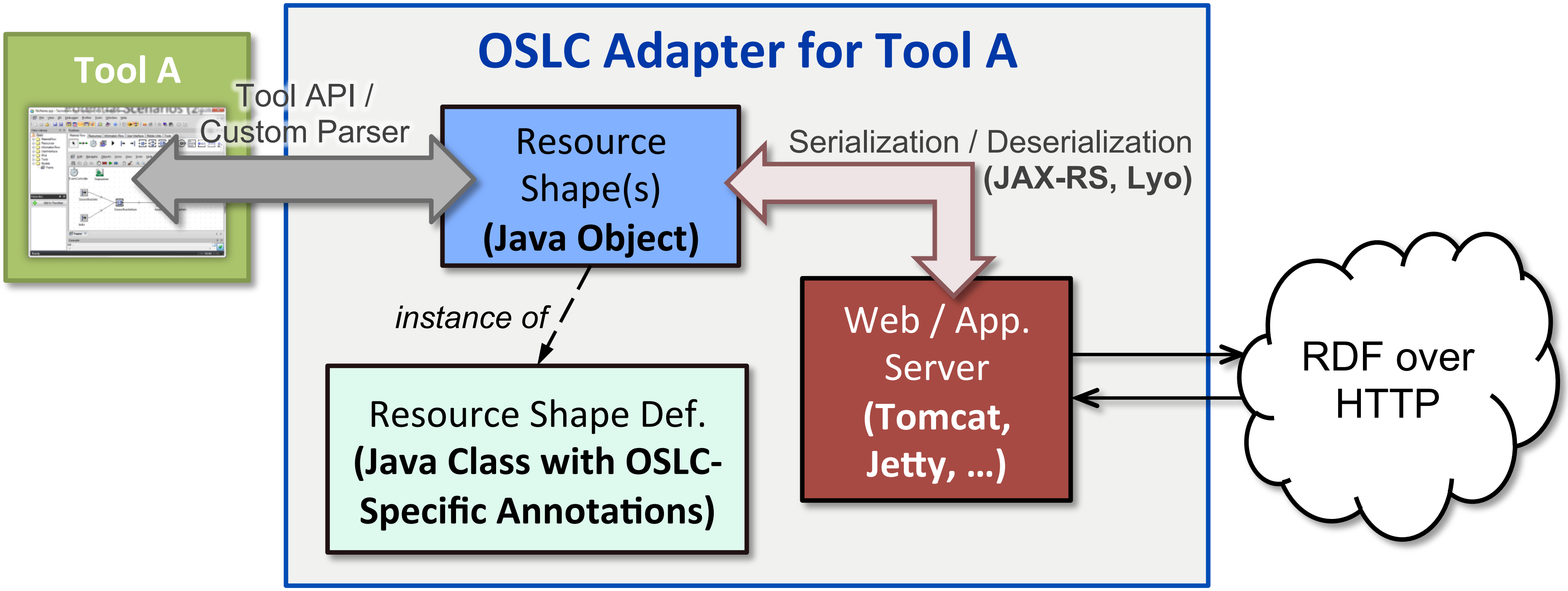
"An inconsistency is present if there is an element x of type Aircraft that is associated through the relation 'has' to at least two elements 'y' of type TurbojetEngine"



ConSystent – Overview of Architecture



OSLC Tool Adapters in Java in a Nutshell



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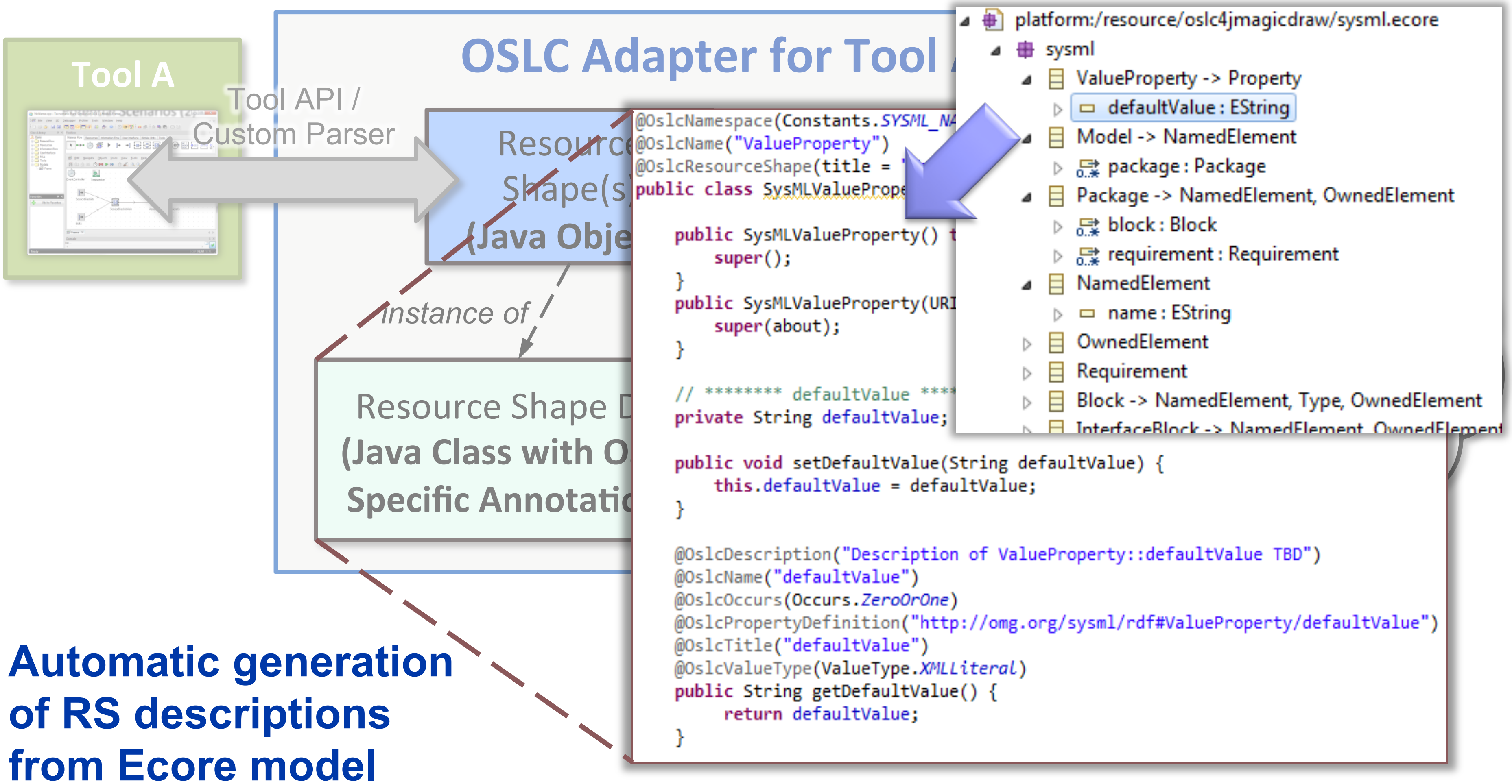
OSLC Tool Adapters in Java in a Nutshell



```
@OslcNamespace(Constants.SYSML_NA
@OslcName("ValueProperty")
@OslcResourceShape(title = '
public class SysMLValuePrope

    public SysMLValueProperty() t
        super();
    }
    public SysMLValueProperty(URI
        super(about);
    }

    // ******** defaultValue ****
    private String defaultValue;

    public void setDefaultValue(String defaultValue) {
        this.defaultValue = defaultValue;
    }

    @OslcDescription("Description of ValueProperty::defaultValue TBD")
    @OslcName("defaultValue")
    @OslcOccurs(Occurs.ZeroOrOne)
    @OslcPropertyDefinition("http://omg.org/sysml/rdf#ValueProperty/defaultValue")
    @OslcTitle("defaultValue")
    @OslcValueType(ValueType.XMLLiteral)
    public String getDefaultValue() {
         return defaultValue;
    }
```

```
platform:/resource/oslc4jmagicdraw/sysml.ecore
  sysml
    ValueProperty -> Property
      defaultValue : EString
    Model -> NamedElement
      package : Package
    Package -> NamedElement, OwnedElement
      block : Block
      requirement : Requirement
    NamedElement
      name : EString
    OwnedElement
    Requirement
    Block -> NamedElement, Type, OwnedElement
    InterfaceBlock -> NamedElement, OwnedElement
```

Automatic generation of RS descriptions from Ecore model

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OSLC Tool Adapters in Java in a Nutshell

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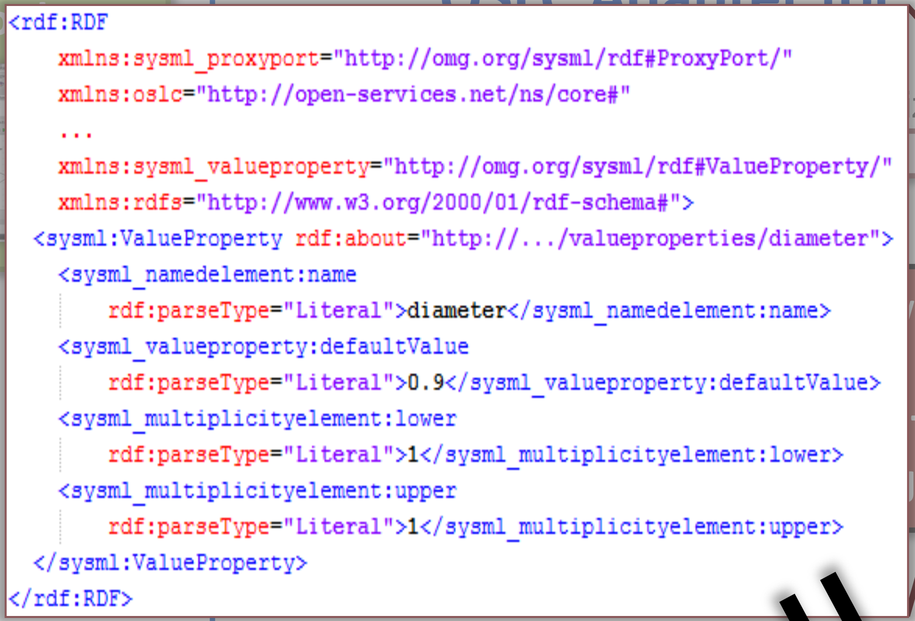
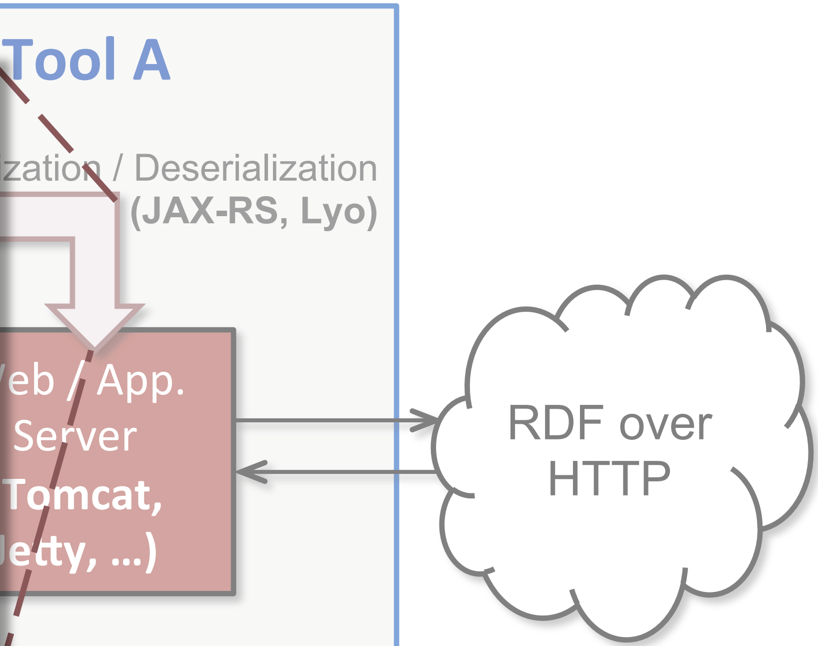
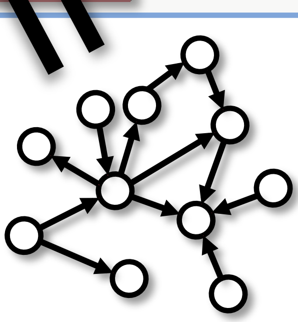


```
<rdf:RDF
   xmlns:sysml_proxyport="http://omg.org/sysml/rdf#ProxyPort/"
   xmlns:oslc="http://open-services.net/ns/core#"
   ...
   xmlns:sysml_valueproperty="http://omg.org/sysml/rdf#ValueProperty/"
   xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#">
 <sysml:ValueProperty rdf:about="http://.../valueproperties/diameter">
   <sysml_namedelement:name
       rdf:parseType="Literal">diameter</sysml_namedelement:name>
   <sysml_valueproperty:defaultValue
       rdf:parseType="Literal">0.9</sysml_valueproperty:defaultValue>
   <sysml_multiplicityelement:lower
       rdf:parseType="Literal">1</sysml_multiplicityelement:lower>
   <sysml_multiplicityelement:upper
       rdf:parseType="Literal">1</sysml_multiplicityelement:upper>
 </sysml:ValueProperty>
</rdf:RDF>
```





Serialization of resource shape in various formats (e.g., RDF/XML, TTL, HTML)

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